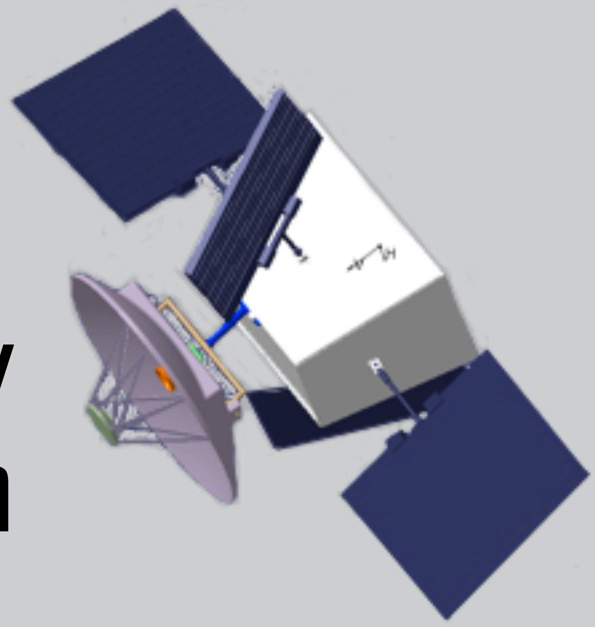
# Radio Astronomy on the Moon

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**Section I.**

# Radio Astronomy on the Moon

## Mission Duration: December 2017 – December 2022


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**Section V.**

**Certification of Compliance with Applicable Executive Orders and U.S. Code**
By submitting the proposal identified in the Cover Sheet/Proposal Summary Information in response to this Research Announcement, the Authorizing Official of the proposing organization (or the individual proposer if there is no proposing organization) as identified below:

- certifies that the statements made in this proposal are true and complete to the best of his/her knowledge;
- agrees to accept the obligations to comply with NASA award terms and conditions if an award is made as a result of this proposal; and
- confirms compliance with all provisions, rules, and stipulations set forth in the two Certifications and one Assurance contained in this NRA (namely, (i) the Assurance of Compliance with the NASA Regulations Pursuant to Nondiscrimination in Federally Assisted Programs, and (ii) Certifications, Disclosures, and Assurances Regarding Lobbying and Debarment and Suspension).

Willful provision of false information in this proposal and/or its supporting documents, or in reports required under an ensuing award, is a criminal offense (U.S.Code, Title 18, Section 1001).

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**Section VII. Summary**


Lunar Innovations (LI), consisting of students from The University of Alabama in Huntsville (UAHuntsville), College of Charleston (CoC), and north Alabama high schools, has designed a mission based on the Radio Astronomy on the Moon (RAM) mission. This mission has two primary objectives. The first objective, from the NASA Science Mission Directorate, is to "assemble an array of radio astronomy telescopes on the far-side of the Moon." The second mission objective, from the NASA Exploration System Mission Directorate, is to "utilize precision landing technologies to land on the far-side of the Moon." LI has chosen to use 130 crossed dipole radio telescopes, referred to as a Lunar Radio Telescopes (LRT), to accomplish its radio astronomy objectives. These LRTs will provide the opportunity to further mankind's

understanding of the fundamental physical processes of the space environment.  Each LRT will weigh approximately 3.8 kg and will be setup in a “Y” shaped array.  The location of the array will be in the Daedalus crater on the far side of the Moon. This location was chosen because it provides maximum shielding from Earth generated radio frequency interference.  To accomplish the precision landing objective, LI will include the Autonomous Landing Hazard Avoidance Technology (ALHAT) on its Landers.  LI decided to use two Government provided Atlas V 551 Launch Vehicles (LV).  In order to increase the overall reliability of the mission, LI has designed each Flight Vehicle with identical configurations.  Each configuration consists of the Flight Vehicle staging, Orbiter, Lander, mobility system, and scientific payload.  The payload on each Lander will consist of the mobility system Mini All-Terrain Hex-Limbed Extra-Terrestrial Explorer (MATHLETE), 65 LRTs, and other science equipment that will be used to study the geological and electromagnetic properties of the lunar surface to see how it potentially affects radio astronomy on the Moon.

*Lunar Innovations Fact Sheet*

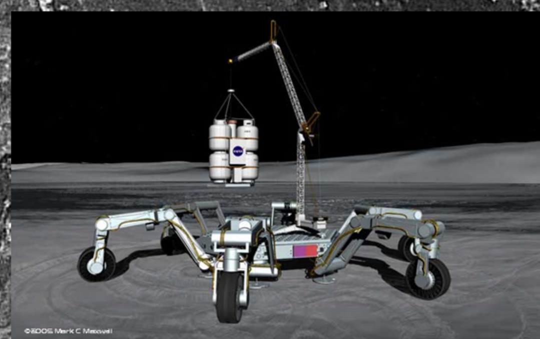
# Radio Astronomy on the Moon

## Mission Overview

• Launch from Cape Canaveral 2017 on Atlas V 551 LV
•Orbiter breaks from Flight vehicle and establishes lunar orbit
• Lander breaks from Flight vehicle and uses ALHAT to land in Daedalus Crater on far side of Moon
• MATHLETE deploys Lunar Radio Telescopes and conducts experiments on geological properties of lunar surface in Daedalus crater

## Mission Cost

1 Flight Vehicle – $682.6 mil
2 Flight Vehicle – $908.9 mil



## Science Objectives

• Map and analyze the structure of the interstellar medium from the local bubble to the galactic center.
• Investigate the mechanisms of solar particle high energy acceleration associated with coronal mass ejections (CMEs).
•Explore the nature and evolution of solar high energy phenomena, the heliosphere, and the solar wind.
• Detect and study enhanced high energy particle acceleration in the heliosphere.
• Identify and study neutrino interactions with the lunar subsurface.
• Detect and study ultra-high energy cosmic rays that collide with the Moon.
• Map the local lunar geological subsurface structure.
• Investigate the electromagnetic properties of the lunar surface.
• Record and study seismic activity on the moon that results from Moon quakes and impacts.

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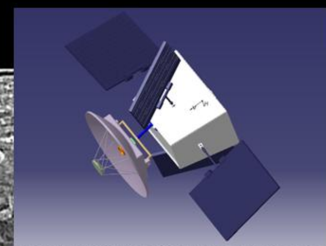
*Lunar Innovations Fact Sheet*

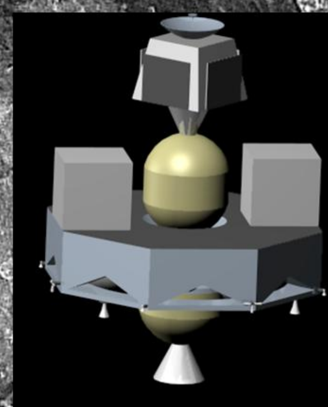
## Key Spacecraft Characteristics

- Autonomous Landing and Hazard Avoidance Technology (ALHAT)
- Mini All Terrain Hex-Limbed Extra Terrestrial Explorer (MATHLETE)



## Science Instruments

- Lunar Radio Telescope (LRT)
- Ground Penetrating Radar (GPR)
- Seismometer
- Electrometer
- Magnetometer



## LI Mission Management

- Project Manager – Alex Antonison - UAHuntsville
- Principal Investigator – Philip Meyer – College of Charleston
- Lead Systems Engineering – Richie Nagel - UAHuntsville
- Chief Engineer – Kirby Vail – UAHuntsville

# Schedule

| 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 |
|---|---|---|---|---|---|---|---|---|
| Phase A | Phase B | Phase C | Phase D | Phase E | Deploy LRT | | Collect Data | |
| | PDR | CDR | | Launch | Land on far side of Moon | | | |

**Section VIII. Required Proposal Summary Information**

- NO proprietary/privileged information included in this application.
- This project DOES involve actives outside the U.S. or partnership with non-U.S. collaborators. The collaborator was ESTACA.
- NO NASA civil servant personnel participating as team members on this project (include funded and unfunded).
- This project DOES NOT have an actual or potential impact on the environment.
- Has an exemption been authorized on an environmental assessment (EA) or an environmental impact statement (EIS) been performed? No
- This project DOES NOT have the potential to affect historic, archeological, or traditional cultural sites or historic objects.

**Section IX.**

- Short title of proposal - RAM
- Type of institution - University
- Identification of target of investigation – Radio Astronomy
- Which launch vehicle performance class is proposed? —Standard with 5m fairing
- Is the use of NEXT proposed? — No
- Is the use of AMBR proposed? — No
- Is the use of aerocapture proposed? — No
- Is the use of ASRG proposed? — No
- Is use of radioisotope heater units, or radioactive material sources for science instruments proposed? – No
- Is a student collaboration (SC) proposed? — Yes
- Is a science enhancement option (SEO) proposed? — No
- Statement of contributions to development or operations (but not science) by any non-U.S. partner. Identify the non-U.S. partner(s), the non-U.S. funding agency/agencies, and the approximate value of the non-U.S. contributions, if any;
- PI-Managed Mission Cost in $ 922.15 Million FY 2010 dollars (Please refer to Section H for Cost Methodology)
- Answers to the following questions:
    i. This proposal contains information and/or data that are subject to U.S. export control laws and regulations, including Export Administration Regulations (EAR) and International Traffic in Arms Regulations (ITAR). – No
    ii. The export-controlled material (EAR and/or ITAR) has been identified in this proposal. – N/A
    iii. The proposer acknowledges that the inclusion of such material in this proposal may complicate the Government's ability to evaluate the proposal. – N/A

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## D. Science Investigation – College of Charleston

A lunar radio observatory offers many advantages over Earth and space based observatories, as well as many opportunities for scientific advancement. The geologically stable far side of the Moon is protected from all Earth based radio sources, which constantly interfere and/or completely obscure radio observations. Furthermore, the Moon lacks a significant atmosphere, which would permit radio observations well below Earth's plasma cutoff (25). To date, this frequency regime has only been successfully observed by satellites lacking in resolution. Lunar Innovations proposes two scientific goals aimed at optimizing the scientific payoff of a lunar radio observatory, found in Science Traceability Matrix Table 1 and discussed in greater detail in the following subsections.

To accomplish these goals a suitable location had to be found. Daedalus was chosen due to its relatively flat surface open space, see Figure1 Daedalus. Furthermore, Daedalus is nearly in the center of the lunar far side on the equator (coordinates, 5.9 ° S and 179.4 ° E). This ensures that there is little chance of stray radio signals from satellites orbiting the Earth. This site also ensures provides a clear view of the Sun and an ideal vantage point for observing the interstellar medium with respect to the galactic plane.

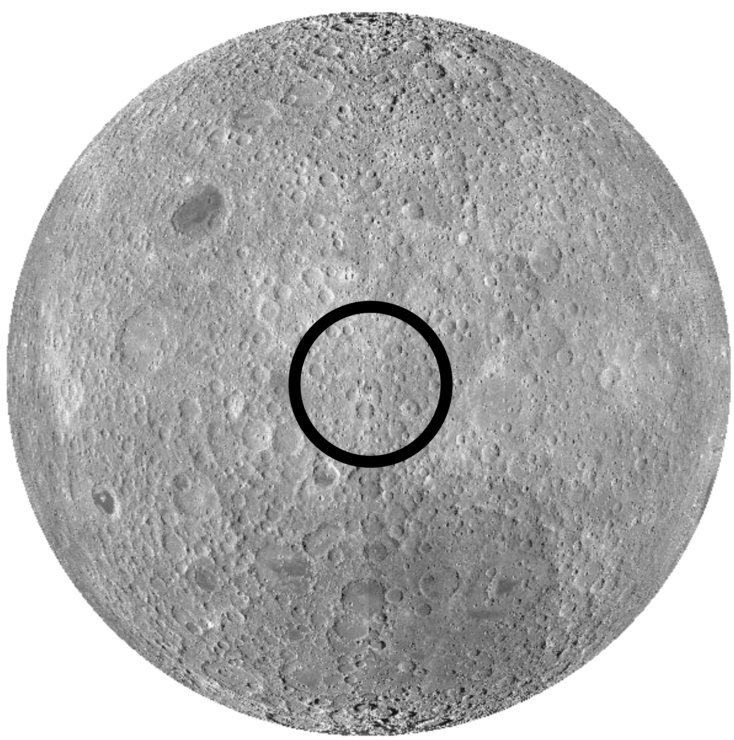

**Figure 1. Far side of the Moon. Circled area location of Daedalus crater.**

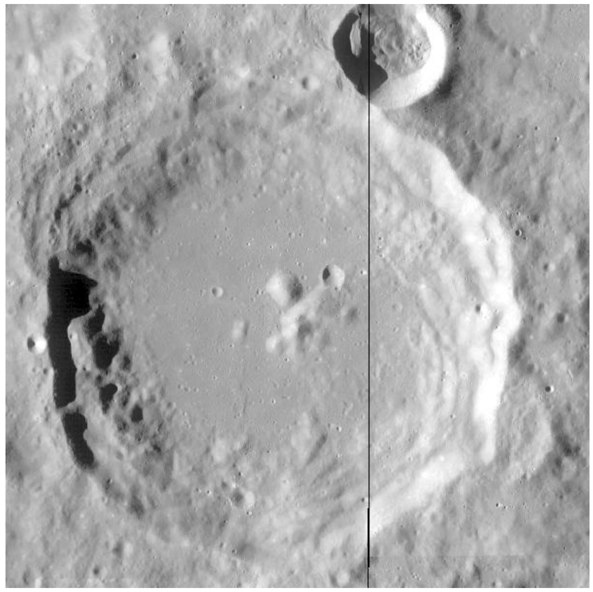

**Figure 2. Image of Daedalus crater**

## D.1. Science Background, Goals, and Objectives

The far side of the Moon provides unprecedented opportunities for astronomers to explore the universe. Furthermore, in the words of Yuki Takahashi, a respected authority on the Moon as a future observatory location, "the Moon has a unique potential for inspiring and uniting everyone on Earth because it is the one common object, save the Sun, that virtually everyone sees regularly $_{(33)}$." Low frequency radio astronomy, in particular, would benefit greatly from the lunar far side environment, allowing study of the last unexplored region of the electromagnetic spectrum.

The far side of the Moon can provide freedom from man made radio signals which are used in our daily lives in the form of television broadcasts, communications, and even our microwave ovens. As an example, a relatively complete list of such sources can be found in FCC allocation table found in Figure 3. This is in addition to naturally occurring radio signals like the intense auroral kilometric radiation (AKR) that result from charged particles in the solar wind getting caught up in Earth's magnetic field. Another natural phenomena that is entirely unavoidable is the Earth's obscuring atmosphere. The ionosphere partially reflects frequencies below 50 MHz, this is the premise that makes long range radio communication possible on Earth, and completely reflects frequencies below 10-30 MHz, referred to as the ionospheric or plasma cut off $_{(33)}$. The far side of the Moon is a haven from all the aforementioned undesirable radio frequency interference (RFI) and with a plasma cut off frequency of approximately 0.3 kHz, would not be obscured by the same constraints found on Earth

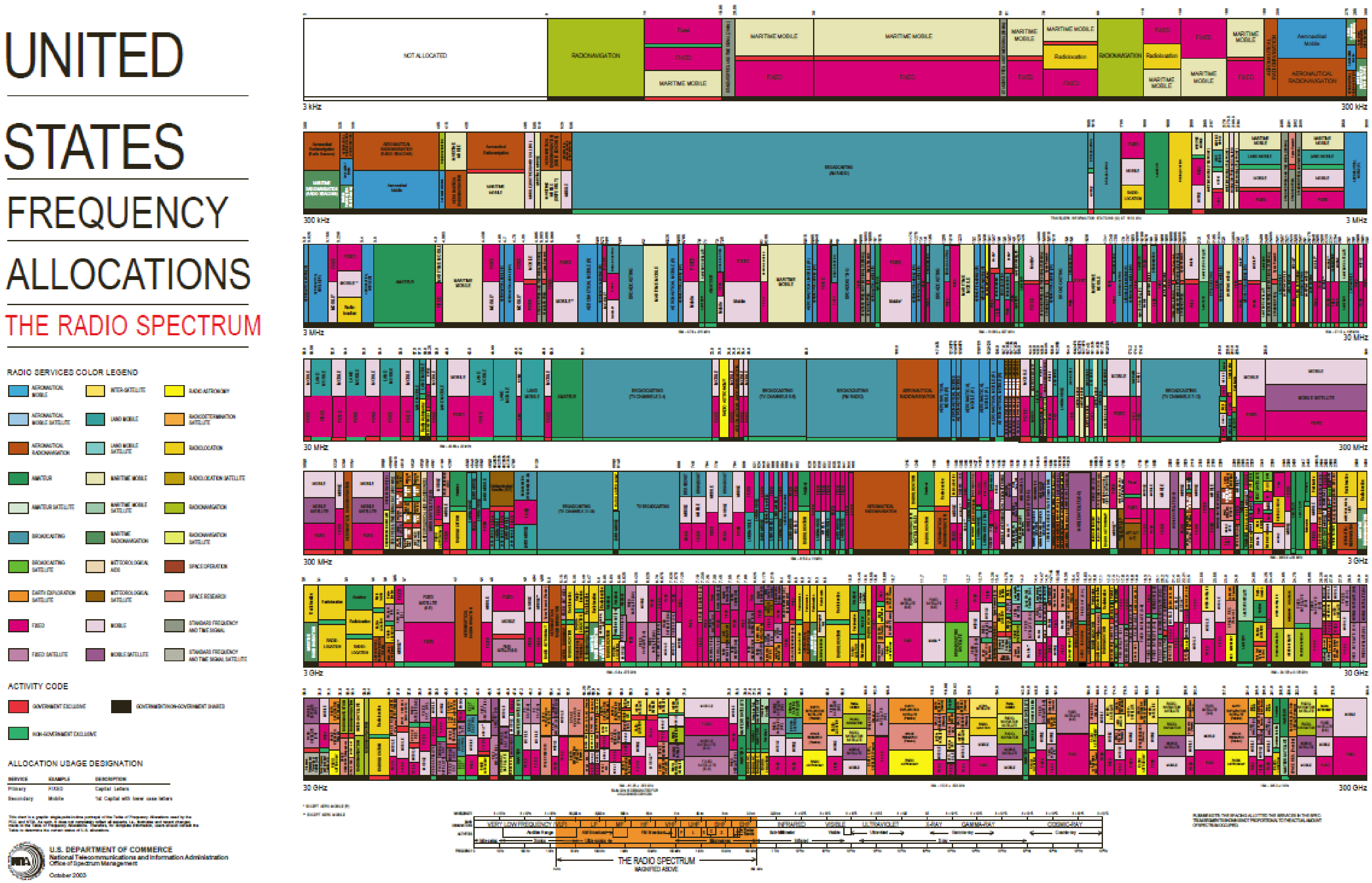


**Figure 3. FCC Allocation Table**

The Moon's large and geologically stable surface are important benefits as well, especially when considering the alternative orbiting array that would require a great deal of precision and complexity without the hope of future expansion. The available space makes it possible for a very large baseline (VLB) array to be established in phases over the course of many years, a feat impossible to accomplish with current technology in a single mission. This is important because interferometry requires a great deal of separation at their farthest points, called the maximum baseline, to achieve the angular resolution required to make useful observations of objects and events at great distances or that occur in a very small region. Building up to a VLB array would allow astronomers to peer farther into space and time (25).

In addition to the observational benefits, radio telescopes are far more robust and durable when compared with telescopes designed for observations at other wavelengths. A particularly good case is the optical telescope. Optical telescopes require sensitive optics that are highly susceptible to the fine particles of dust that exist on the moon. Furthermore, a single impact of a meteor with the optics would result in catastrophic failure. Radio telescope elements are composed of a crossed dipole, which is essentially a set of two metal rods, receiver, and correlator. The receiver can be very small and easily shielded from the thermal and radiation environment. The correlation can be done at a remote location so shielding is not problematic. The benefits, cost, simplicity, and durability of a radio telescope array cannot be matched by observatories at other wavelengths (25).

### *D.1.1. Background*

The Sun is a variable and highly energetic place that has a great deal of impact on the Earth and the local space environment. At any given moment, a nearly constant flow of energetic particles, most notably electrons and protons, are emitted by the Sun. This flow of charged particles, known as the solar wind, can vary greatly in speed and intensity with the occurrence of highly energetic phenomena like coronal mass ejections (CMEs) (35). These events are bursts of magnetic fields and plasmas. Plasmas are comprised of matter that has been ionized, or the bonds of its constituent charged particles have been broken and the particles separated in space. This charge separation results in electric fields that, when varied in time, result in magnetic fields. When directed at Earth, these intense fields can affect electronics, particularly those in orbit, the power grid, and are even responsible for large fluctuations in the aurora borealis, which is caused by magnetic reconnection in the Earth's magnetotail that permits charged particles to enter the Earths' atmosphere. These intense fluctuations in the solar wind are what are referred to as magnetic storms and are one of several events responsible for space weather.

The solar wind is responsible for the bubble, called the heliosphere, in which the interplanetary medium (IPM) and the solar system lie (36). See Figure 4**.** This bubble, inside the larger interstellar medium (ISM), is primarily made up of material that originates in the Sun. As this material approaches the boundary between the heliosphere and the ISM, the particle velocity is decreased dramatically, this is known as the termination shock. Similarly, the point where interstellar particles slow dramatically is known as the bow shock. These two points are separated by the heliopause, where the resulting pressures are in equilibrium. The structure of the heliosphere is determined by two competing pressures from the solar wind and the winds of interstellar space, and defines the boundaries of the IPM. The interstellar wind is the result of stellar winds and expanding supernova. Due to variability in the solar wind and interstellar wind, the heliosphere's structure is constantly changing.

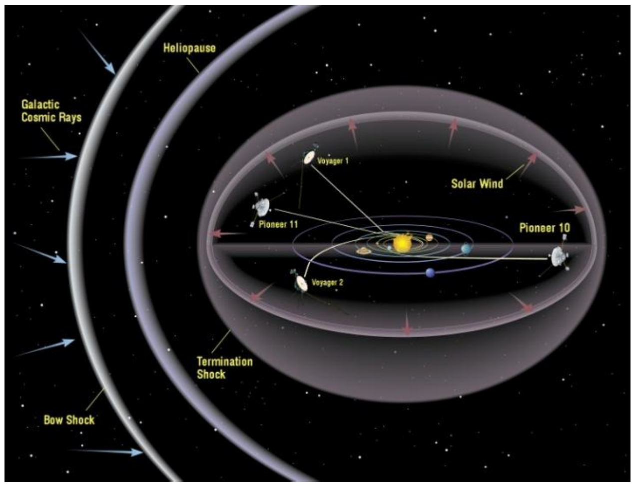


**Figure 4. Heliosphere**

The ISM is composed of multiple phases that are differentiated based on whether the matter is ionic, atomic, and molecular, as well as temperature and density of the matter. This matter includes interstellar dust and cosmic rays. The matter is gathered in bubbles or clumps of similar temperature, density, and phase, and this how they are characterized. The solar system lies within one of these bubbles, referred to as the local bubble. Many theoretical models have been built based on the limited data available, but no complete mapping of the structure of the ISM has been completed due to the observational constraints. The space born predecessors of RAM, including RAE 1 and 2, were incapable of reaching angular resolutions of better than 30 degrees (45). RAM will be capable of better than two arcminutes of angular resolution. This means that RAM will outperform any other radio telescope in existence at its designated frequency bands.

#### *D.1.2. Goals*

NASA's 2010 Science Plan asks, "How and why does the Sun vary and affect Earth and the rest of the solar system?" To address this question, Lunar Innovations intends to further our understanding of "...the fundamental physical processes of the space environment from the Sun to Earth, to other planets, and beyond to the interstellar medium," through a mission entitled Radio Astronomy on the Moon (RAM). Furthermore, RAM's instrument complement will advance our understanding of the lunar surface and subsurface properties. This will include data about the electromagnetic and seismic properties of the lunar surface, as well as subsurface morphology. Not only will this information provide incite into the proposed radio observations, but it will be an important addition to the body of knowledge regarding the Moon's formation history and weak magnetic field. Moreover, this data will be significant to future human operations on the Moon, currently being considered.

### *D.1.3. Objectives*

#### D.1.3.1. RAM will map and analyze the structure of the interstellar medium (ISM) from the local bubble to the galactic center.

Peterson and Weber have been able to model the clumpiness of the warm ionized medium (WIM) phase of the ISM (47). This modeling of the free electron distribution was accomplished by comparing the expected turnover in the Galactic synchrotron emission to observation made by RAE 2 and IMP 6. This method involves a knowledge of the intrinsic, unabsorbed shape of the synchrotron emission spectrum and the observed brightness distribution. This method is applicable over the frequency range of 0.1 to 10 MHz.

Jester and Falcke have proposed extending this model to infer the actual three dimensional structure of ISM (45). This will be done by using the relationship between ISM "visibility" as a function of Galactic latitude for different frequencies and the limiting power law for the line of sight distance as a function of frequency. This relationship dictates frequency ranges given by the equations. By scanning through these frequencies and modeling the observed emissivity as a function of Galactic coordinates, the three dimensional structure can be determined. At these low frequencies, the actual substructure of the ISM will set the visibility rather than the global structure This map of the ISM will provide a great deal of incite into the structure of the galaxy and be an excellent tool in understanding the evolution of the Milky Way galaxy.

$$D(\tau = 1) = 100\ pc(\frac{n_e}{0.132cm^{-3}})^{-2}(\frac{T_e}{7000K})^{3/2}(\frac{\nu}{1MHz})^2$$

#### D.1.3.2. RAM will investigate the mechanisms of solar particle high energy acceleration associated with coronal mass ejections (CME).

High-energy particle accelerations are a regular occurrence in many astrophysical environments including the Sun. CME driven shocks are known to create disruptions in the solar wind, increased cosmic ray intensity for example (45). However, there is still little understood about the actual mechanisms of accelerations, including magnetic reconnection and the shocks driven by CMEs, called Type II bursts (34-39).

Accompanying these high-energy accelerations are intense radio bursts that are easily observed in the low frequency spectrum (46). These intense bursts can be localized using RAM's resources to a degree never before possible. Currently, these events can only be localized to a region one tenth the diameter of the sun. RAM will be capable of improving that localization by a factor of ten with its less than 0.5˚ of angular resolution at 1 MHz.

Questions about the geometry between shock front and magnetic field can be answered using the high degree of localization available to RAM (46). Bale et al have hypothesized that electron acceleration generally occurs when the magnetic field and the normal vector of the shock are perpendicular (48). This hypothesis has been challenged by geometric arguments that suggest a quasi-parallel geometry. However, according to MacDowall, a quasi-perpendicular geometry is the more likely location for Type II emission (46). RAM will be more than capable of the approximately 2˚ resolution required to determine the relationship between the shock front and magnetic field.

#### D.1.3.3. RAM will explore the nature and evolution of solar high energy phenomena, the heliosphere, and the solar wind.

CME activity is currently only available out to approximately two solar radii. RAM's low frequency, omnidirectional array will be capable of observations out to one half astronomical unit (AU), one hundred times better than the observations made by small satellite based antenna. This live tracking will make use of the fact that frequency slowly falls off with density and therefore radius as the energetic particles travel into the heliosphere, also known as the solar wind (44). This localization and tracking of the solar wind through the heliosphere will play a crucial role in future space weather predictions.

#### D.1.3.4. RAM will detect and study enhanced high energy particle acceleration in the interplanetary space.

This enhanced high energy particle acceleration is the result of two or more CMEs interacting in the interplanetary space (40 and 41). This collision results in unusual radio signatures that can be picked up by RAM. Little is known about the nature of such an interaction and the solar energetic particle (SEP) intensity due to a lack of radio imaging. However, it is theorized that changes in field topology, enhanced turbulence, or direct interaction could be responsible (46). Understanding these events will contribute a great deal to high energy particle physics, as well as provide information necessary for their predictions.

#### D.1.3.5. Observe ultra-high energy cosmic rays (UHECRs) that collide with the Moon.

These ultra-high energy particles, composed of protons, atomic nuclei, and potentially photons or neutrinos, are a potential threat to man's presence in the space environment. The total flux associated with cosmic rays is about 1 particle per meter squared per sterad per year above the baseline particle energy of $10^{16}$ eV (45).

These UHECRs can be observed indirectly by examining the intense particle cascade that occurs when they interact with dense matter, like the surface of the Moon. When they interact with the surface they are traveling at speeds greater than the local speed of light of the lunar regolith, for example, leading to Cherenkov light (42 and 43). The resulting radio observations will be short, coherent, and can be triangulated when observed by three or more dipoles.

#### D.1.3.6. Identify neutrino interactions with the lunar subsurface.

The arguments used for deriving the radio flux generated by UHECRs also apply to neutrino interactions, so that the array parameters are identical for the detection of both neutrinos and more massive cosmic rays. The largest difference will be the penetration depth, as the mean free path for a neutrino is 130 km. In this respect, low frequency radio waves have a much higher probability of detecting them when compared with other wavelength regimes. A single dipole will be capable of seeing a detector volume, in this case the lunar soil, of approximately 1.5 $km^3$.

#### D.1.3.7. RAM will map the local lunar geological subsurface structure.

The lunar subsurface morphology will be an important part of interpreting the received radio data as reflection are likely to be observed (44). The two dimensional structure will be determined using ground penetrating radar that will emit radar then pick up the reflected signal using time to determine penetration depth. This penetration depth will change based on the underlying structure. Moreover, these two dimensional slices of the subsurface structure can be combined as the system samples over a given distance to create a three dimensional map. In addition to its applications to the radio astronomy, this map can be used to uncover past crater impacts that have long been covered.

#### D.1.3.8. RAM will investigate the electromagnetic properties of the lunar surface.

The electromagnetic properties of the lunar surface are an important part of the RAM mission as these properties could directly influence the radio signals observed. Furthermore, this site specific data will be used to uncover potential resources for future manned missions.

#### D.1.3.9. RAM will record and study seismic activity on the moon that results from moon quakes and impacts.

Seismic activity on the Moon is small relative to the Earth with ground motion on the scale of microns. However, seismic activity resulting from Moon quakes and meteor impacts have recently been discovered to emit electromagnetic radiation (49). These wavelengths have the potential to interfere with radio telescope observations. Additionally, the seismometers can be used in conjunction with the radio array to prove or disprove theories of using radio telescopes to monitor seismic activity.

### D.2. Science Requirements

RAM will be observing electromagnetic waves produced by particles in the ISM. This will require a frequency range of 0.1 to 10 MHz to observe the relevant emissions. To achieve the required one degree of angular resolution, RAM will deploy 130 crossed dipole units, including margins, with maximum baselines of 30 km. This objective will require an in integration time of approximately one year over which time frequency, amplitude, phase, and polarization will be recorded at a sensitivity of 10,000 K. Once returned to Earth for analysis, the data will be normalized using the calibration data, then the spectral turn over at each of the predetermined frequencies will be identified and used to create the three dimensional topographical map.

RAM will be observing radio emissions that occur in the Sun's corona as well as in the heliosphere. These observations will require a frequency range of 1 to 10 MHz with less than one degree of angular resolution and a sensitivity of 1 MJy. This will be accomplished through the same deployment discussed in the previous section and measuring the same physical parameters. Similarly, the data will be normalized on Earth. The radio emission profile will be used to track the events directly providing location, while simultaneously creating an instantaneous density profile. The method is the same for all three of the solar objectives.

RAM will be observing high energy particle interactions with the lunar surface and subsurface. This will require a frequency range of 10 to 30 MHz, an angular resolution of less two degrees and a sensitivity of 100 MJy. This is accomplished using the previously described deployment and physical parameters, and includes the required maximum spacing of 5 km. These short coherent bursts will be identified by their short and intense radio bursts. Once identified, these observations will be used to quantify both cosmic ray and neutrino interactions with the lunar surface, and will be differentiated by their period.

RAM will map the lunar subsurface. This will require a 0.1 meter resolution. This objective will be accomplished by using ground penetrating radar that will emit a radar pulse and measure the time of return. The pulse will be identified by its frequency and amplitude. This data, once returned to Earth will be used to create two dimensional cross section of the subsurface, then compiled to produce a three dimensional map.

RAM will investigate the lunar surface's electromagnetic properties through the use of an electrometer and magnetometer. This will require the measurements of electric and magnetic field/flux to a sensitivity of 1pC and 1 μG respectively. The electrometer will detect material charging effects, ion currents, electric fields and temperature readings of the lunar regolith. The fluxgate magnetometer will generating drive, sense and feedback signals from the sensors. The drive signal will detect the second harmonic of itself, null the field of the sensor and provide the digital reading of the current that was required to null the sensor field. Data from both units will be returned to Earth and the raw data used to characterize the electric and magnetic properties of the surface material with respect to conditions, such as location and temperature.

RAM will record the seismic activity that occurs on the Moon in real time. This objective will require that the seismometer have a frequency range of 0.05 mHz to 50 Hz. The physical measurements will be the frequency and amplitude of waves associated with ground movement. The ground movement will be plotted as a function of time to characterize the seismic environment and significant events will be correlated with telescope observations.

# Table 1. Science Traceability Matrix

| Science Goals | Science Objectives | Scientific Measurement Requirements | | Instrument Functional Requirements | | Mission Functional Requirements (Top Level) |
|---|---|---|---|---|---|---|
| | | Observables | Physical parameters | | | |
| Further our understanding of the fundamental physical processes of the space environment from the Sun to Earth, to other planets, and beyond to the interstellar medium (ISM). | Map and analyze the structure of the interstellar medium from the local bubble to the galactic center. | Free-free emission | Frequency, amplitude, phase, and polarization | Freq. Range | $0.1 < f < 10$ MHz | N ~ 100 dipoles |
| | | | | Angular Resolution | ~ 1 degree | 30 km baseline |
| | | | | Expected Signal | 10,000 K | Integration time of ~1 year (5-σ) |
| | Investigate the mechanisms of solar particle high energy acceleration associated with coronal mass ejections (CMEs). | Free-free, cyclotron, synchrotron, and plasma radio emission | Frequency, amplitude, phase, and polarization | Freq. Range | $1 < f < 10$ MHz | N ~ 100 dipoles |
| | | | | | | 0.5-30 km baselines |
| | Explore the nature and evolution of solar high energy phenomena, the heliosphere, and the solar wind. | | | Angular Resolution | ~ 1 degrees | Transient observables |
| | Detect and study enhanced high energy particle acceleration in the heliosphere. | | | | | Data acquisition may be triggered |
| | Identify and study neutrino interactions with the lunar subsurface. | Coherent Radio Emission | Frequency, amplitude, phase, and polarization | Freq. Range | $10 < f < 30$ MHz | N ~ 3 - 100 crossed dipoles |
| | | | | Angular Resolution | < ~ 2 degrees | Transient observables |
| Further our understanding of the lunar space environment to discover potential hazards to humans and to search for resources that would enable human presence. | Detect and study ultra-high energy cosmic rays that collide with the Moon. | | | Sensitivity | 100 MJy | Maximum 5 km spacing |
| | Map the local lunar geological subsurface structure. | Radar Reflection | Frequency and amplitude | Resolution | ~ 10 cm | Radar instrumentation and telescope should not operate simultaneously |
| | Investigate the electromagnetic properties of the lunar surface. | Electric and Magnetic Field | Electric and Magnetic Field/Flux | Sensitivity | ~ 1 µG, ~1pC | |
| | Record and study seismic activity on the moon that results from Moon quakes and impacts. | Seismic Waves | Frequency and amplitude | Freq. Range | 0.05 mHz - 50 Hz | |

### D.3. Threshold Science Mission

RAM's threshold mission requires that at a minimum of 50% of the dipoles function with 15 km baselines. Below this the mission is not worth pursuing. All baseline mission objectives, with the exception of the ISM mapping, can still be achieve, albeit at a lower resolution for the solar studies. This lower resolution would mean that valuable data regarding the solar studies could still be returned, but that this data will result in limited conclusions.

## E. Science Implementation – College of Charleston

### E.1. Instrumentation

In order to accomplish the science objectives stated in the science investigation section of this proposal, a combination of instruments will be required. The most important of these instruments being a radio astronomy interferometry array that will have the ability to pick up very low frequencies within the very low end of the radio sector in the electromagnetic spectrum. Also, this array must be completely free of any terrestrial radio frequency interference (RFI) from the Earth as well as free of a thick ionosphere. To accomplish these requirements, the array must be placed on the far side of Moon.

Even Though the Moon is the best place to have a VLF radio array, the environment of the Moon must be evaluated as well to see what effects it will have on the gathering of so that the VLF data can be properly interpreted. To monitor the environment of the array's site, seismometers, GPRs, magnetometers and electrometers will be integrated into the mission's implementation. This section will describe each instrument used in the setup, what each will be used for, and how they correlate with the science objectives of the mission.

#### *E.1.1. Radio Telescope*

For this mission, a radio telescope consisting of a baseline of 130 crossed dipole units (threshold: 65 units) will be implemented within the Daedalus crater on the far side of the Moon and will operate at a mission critical frequency range of 0.1 MHz to 16 MHz. These units will be spread out in even intervals in a Y-shaped architecture with each arm stretching out to a 30 km baseline for simplicity of deployment. A crossed dipole implementation was chosen because crossed dipoles in radio telescopes are able to detect and identify polarized and non polarized radio emissions, and this mission's science objectives require identification of polarization. The radio telescope will also consist of receiver units that take heritage from the WAVES and STEREO experiments on the WIND mission. The following subsections will go into more detail on the crossed dipole units and the receiver units.

##### E.1.1.1. Crossed Dipole Unit

After considering many conceptual designs, it has been decided that the mission will implement the ESA design discussed by Yuki Takahashi for a crossed dipole unit (33). This design was chosen because it is designed to handle a frequency range close to this mission's range, its mass requirements were reasonable, and the length of the dipole antennae were reasonable as well. The design does not meet the exact specifications needed for this mission, but the specifications are so close that the design can be altered. The mass of the dipole unit in ESA design is 5 kg which includes all underlying receiver electronics, dipole antennae materials, UHF communications and transmitter/receiver electronics and thermal shielding. For this mission the ESA design will be altered to fit a 3.8 kg mass per unit using newer technology in order to allow for a greater number of crossed dipoles to be placed on the Moon. With this altered mass, the total mass of the array will come out to be a baseline of 494 kg and a threshold of 247 kg. The underlying electronics for the receiver electronics will be altered as well to fit the desired frequency range.

#### E.1.1.2. Operational Modes

##### *E.1.1.2.1. Data Collection Mode*

The data collection mode for the crossed dipole units will put them in a state of passively listening for low frequency radio wave emissions in the desired 0.1 MHz to 16 MHz range. This mode is activated when the lander sends a signal to the dipoles, indicating that the lander's storage has been dumped. Further details can be found in the Science Mission Profile section of this proposal. This mode will be able to operate simultaneously with the data transmission/receive mode.

##### *E.1.1.2.2. Data transmission/Receive Mode*

The data transmission/receive mode for the units will put the units in a state of transmitting data back to the lander via UHF transmitters after the receiver electronics have amplified and digitized the incoming radio signals. The receiving end of this mode will accept UHF transmissions from the lander for activation, or calibration of the dipole units. This mode will be able to operate simultaneously with the data collection mode.

#### E.1.1.3. Power Demands

Operational Mode power requirement is 1 watt. This consist of 0.5 watts for communications and 0.5 watts for dipoles and electronics. The standby mode requires only 0.5 watts.

#### E.1.1.4. Receiver

There will be receiver electronics for each dipole unit that will serve the purpose of amplifying signals, converting signals to intermediate frequency (IF) and converting signals from analog to digital for communications. The receiver for this mission will consist of a combination of heritage receiver electronics and designs from the WAVE and STEREO experiments. The reasoning behind the selection of receiver electronics from these two experiments is that most of the radio emissions collected by the array will be of solar origin and because they are tuned and ready to handle radio frequencies that closely fit the mission's desired frequency range.

The receiver electronics will be an implementation of the electronics of STEREO since the electronics virtually fit the mission's desired frequency range. The setup of the receiver will then follow the split frequency implementation on the WAVE experiment. By split frequency, meaning that there will be two separate receiver electronic boards with each board taking up a part of the frequency range. For the purposes of this mission, the first board will take the lower end of the frequency which comes out to be 0.1 MHz to 0.9 MHz. The second board will accept the frequency range of 1 MHz to 16 MHz. After the signals have been amplified and converted to IF, the receiver electronics, equipped with 8-bit analog to digital converters, will digitize the signals. This converter has been chosen because it is already a functioning part of the receiver electronics on the STEREO experiment. With receiver electronics already built into the dipole units, the receiver electronics will be altered to fit the mass, dimension and thermal requirements using newer technology (23,32).

#### E.1.1.5. Calibration

Calibration of a lunar array is not as big of a concern as the calibration of a terrestrial based array, but measures of calibration still need to be taken to ensure that the telescope operates nominally. Since the density of the Moon's ionosphere and atmosphere are low, ionospheric calibration will not be a big issue. On the other hand, calibration methods will have to be implemented for gain variations due to the extreme temperatures of the Moon. On top of the environmental calibrations, the telescope will have to be calibrated for the objects it will be looking at in the sky as well. This mission will be focusing on the mapping the ISM and high energy particle acceleration events on the Sun and within the inner heliosphere, so methods will have to be employed in order to calibrate out the frequencies that are not associated with those objects and events.

### *E.1.2. Ground Penetrating Radar*

To study the subsurface structure of the Moon, the mission will be implementing Ground Penetrating Radar on the deployment rovers. To be more specific, the mission will utilize a modified version of the Construction & Resource Utilization Explorer (CRUX) GPR. The CRUX GPR is still being developed by JPL and has been designed for subsurface stratigraphy and prospecting applications on Mars and the Moon. Since it is still undergoing technology readiness (Currently at TRL 4), it will undergo various shake and bake tests at Goddard Space Flight Center.

The CRUX operates by transmitting short pulses into the ground and receiving the different dielectric permittivity readings of different materials at a depth of 5 meters for Moon operations (26). The CRUX consists of two antennae. The transmitting antenna operates at 250 kHz and sends the pulses into the ground. The receiving antenna operates by receiving the pulse reflections. Once the signals have been collected by the receiving antennae, they are amplified and compiled into signals that are machine readable (26).

#### E.1.2.1. Operational Modes

##### *E.1.2.1.1. Transmit/Receive Mode*

When in transmit mode, the transmitting antenna located at the bottom of the CRUX GPR will be sending short pulse RF signals into the soil of the lunar surface at a frequency of 250 kHz. This mode has the ability to operate simultaneously with receiving and signal processing modes.

When in receive mode, the receiving antenna located at the bottom of the CRUX GPR will be receiving the short pulse reflections from the lunar surface and subsurface at the same frequency as the transmitting antenna. This mode has the ability to operate simultaneously with transmit and signal processing modes.

##### *E.1.2.1.2. Signal Processing Mode*

When in signal processing mode, the processor on board will take in the signal and have it amplified and digitized. To digitize the signal, it will be fed through a 10-bit Analog to Digital converter. This mode will have the ability to operate simultaneously with transmit and receive modes.

#### E.1.2.2. Power Demands

Operational mode requires 1 watt. Standby mode requires less than 1 watt.

#### E.1.2.3. Calibration

Calibration for the CRUX GPR will involve determining echo times for the RF signals that are transmitted into the lunar regolith. To calibrate for these echo times, the CRUX will have to be calibrated for the different mineralogical compositions of the Daedalus crater. These compositions can be tested from Earth since there are mineral compositions on Earth that are similar to mineral compositions on the Moon.

### *E.1.3. Magnetometer and Electrometer (Science Wheel)*

For the mission, it is important to understand the electrostatic and magnetic properties of the lunar surface and subsurface in order to analyze what affects these properties will have on the dipole units as they collect radio emissions. To study these properties, the mission will be implementing the Pierce Rowe Fluxgate Magnetometer (PRM) ST5 and the Mars Environmental Compatibility Assessment (MECA) electrometer inside the wheels of the deployment rovers. This will allow for picking up electrostatic and magnetic soil readings while the deployment rovers setup the telescope.

The fluxgate magnetometer will work by generating drive, sense and feedback signals from the sensors that will then transmit back to the lander. The drive signal will detect the second harmonic of itself, null the field of the sensor and provide the digital reading of the current that was required to null the sensor field (30). The electrometer will work by detecting material charging effects, ion currents, electric fields and temperature readings of the lunar regolith. In order to accomplish this, the electrometer will consist of a triboelectric field, electric field, ion current and temperature sensors. The triboelectric field sensor consists of an array of sensors that will be used to detect the charging effects of the soil as the sensors are rolled through the lunar regolith (24). With both the magnetometer and electrometer built inside the wheels of the deployment rovers, their sensors will be exposed to the outside of the wheel in order to take their measurements.

#### E.1.3.1. Power Demands

This requires 0.45 watts for operational mode and requires less than 0.45 watts for standby mode.

#### E.1.3.2. Calibration

The electrometer and magnetometer will have to have their sensors calibrated for the temperatures of the Moon. The electrometer has been initially calibrated for temperatures between -60 degrees Celsius and room temperature, but it will also have to be calibrated for the extreme temperatures of the Moon to see how the sensors react (24). The sensors for the magnetometer will have to be calibrated in a similar way.

### *E.1.4. Seismometer*

Seismometers will be implemented throughout the telescope's setup area in order to detect quakes and evaluate their effect on the telescope's performance. Quakes both shallow and deep will need to be evaluated, so the mission has decided to implement the ExoMars seismometer. This seismometer has not yet been implemented since the ExoMars mission does not launch til 2013, but its TRL level as of 2008 was at level 5, so by the time this mission is implemented, it will be at the required TRL (29). The seismometer will also be operating at a frequency range of .05 mHz to 50 Hz.

#### E.1.4.1. Power Demands

This requires 1 watt to operate and less than 1 watt to be in standby mode.

#### E.1.4.2. Calibration

The ExoMars seismometer will undergo calibrations for temperature and sensitivity. For the extreme temperatures of the Moon, the seismometer will be calibrated for these temperatures to see how the sensors react. The sensitivity of the seismometer will be calibrated to pick up minimum and maximum magnitudes based on previously collected seismic data from the Apollo mission seismometers.

## E.2. Data Sufficiency

This mission will focus primarily on collecting VLF radio emissions in the frequency range of .1 MHz to 16 MHz. More specifically, the waves that will be focused on will come from the interstellar medium and the high particle acceleration phenomena from the Sun. Secondary data will be coming from the lunar environment. This data will consist of subsurface infrastructure stratigraphy, seismic readings and electrical and magnetic regolith properties. Both VLF and lunar environment data will be collected from the lunar surface. The VLF radio emissions will be collected using an interferometry setup of 100 crossed dipole units as stated in section E1 of this proposal. The subsurface, seismic, electrical and magnetic data will be collected using a variety of instruments deployed on the deployment rovers.

### *E.2.1. Quality of Data*

Referencing the Science Investigation portion of the proposal gives an idea about the quality of data that is required to accomplish the science mission goals and objectives. For the radio emissions captured by the lunar ground telescope the quality of data will be better with the higher frequencies and will be of less quality at the lower frequencies. This is due to the setup of the telescope. With the dipole units being spread out in an even fashion across a 30 km baseline, the angular resolution will be at most 4.29 degrees and at the least 1 arc minute, roughly. As it can be seen in the matrix, the highest degree of angular resolution required for collecting radio data is at the most ~2 degrees. For the purposes of this mission, it will be beneficial to collect the highest resolution of data possible in the uninterrupted VLF realm. Table X. gives more detailed information about angular resolution parameters

The quality of data being collected by the seismometers, electrometers, magnetometers and GPRs will be sufficient for this mission.

**Table 2. Frequency and Resolution ranges of points of interest**

| Point of Interest | Frequency Range | Angular Resolution Range |
|---|---|---|
| Interstellar Medium | .1 < f < 10 MHz | 4.29 deg < a < 2.58 arcmin |
| Sun | .1 < f < 30 MHz | 4.29 deg < a < 0.86 arcmin |
| High Energy Particle Acceleration | 10 < f < 30 MHz | 2.58 arcmin < a < .86 arcmin |

### *E.2.2. Quantity of Data*

For the duration of the mission, the quantity of data being collected will be based on a combination of every instrument being utilized for the mission. Most of the data will be collected from the telescope. The following subsections will describe the quantities that each instrument will collect on a daily basis or for a certain distance, the rationale behind those data demand calculations and what the quantity will be by the time the 2 year collection period has ended. Table X gives the quantities in tabular form.

#### E.2.2.1. Lunar Radio Telescope

According to some radio data collection specifications given back Dr. Jack Burns, a dipole unit can roughly collect .5 MB of radio emissions for every minute on the far side of the Moon (25). For the baseline mission this will equate to 65 MB a minute of collection for the radio telescope and a threshold of 32.5 MB a minute. The data storage for mission data on the lander will be able to hold a capacity of 70 GB. With the telescope's data collection rates, the telescope will be able to fill up the storage capacity in a total time of 17.9 hours. At a threshold, the telescope would be able to fill the storage capacity within a total time of 8.95 hours. The time for the telescope to fill up the storage capacity will actually be a little less since the lander's onboard storage will be used for other data collection and storage purposes. At a maximum, the telescope will be able to collect a baseline of 93.6 GB of data a day. This threshold equates to a maximum of 46.8 GB a day. Over the 2 year collection period, the mission will endure a baseline maximum of 63.8 TB of data and a threshold of 34.2 TB of data. It will be kept in mind that these data will be a little less due to the fact that the seismometers will be collecting data simultaneously with the telescope and the GPR will be running operations in between telescope collections.

#### E.2.2.2. Ground Penetrating Radar

Besides the telescope being the most data intensive instrument, the CRUX GPR will be collecting large amounts of data as well. Mapping the distance of one arm on the telescope will require 7.9 GB of data from the CRUX GPR. With the distance of three arms, this rate goes up to 23.7 GB. Since the purpose of the CRUX is to map the entire telescope area, these data demands will be too much to map the whole area before the deployment of the telescope. Depending on the optimization routes taken by the deployment rovers, both CRUXs will gather at least a total of 711 GB of data for the whole area of the telescope. To keep the daily data demand at a minimum, the CRUX will operate in between telescope operations. The collection of this data will be spread out over the 2 year collection period in order to keep data demands reasonable.

#### E.2.2.3. Magnetometer

The magnetometers on the deployment rovers will be able to collect all of the magnetic properties of the soil before the deployment of the radio telescope. The PRM Fluxgate Magnetometer is capable of gather 41.4 MB of data at the length of a 30 km arm. Over three arms this equates to 124.2 MB. In covering the total area of the telescope the magnetometers will collect a total of 11.2 GB. This is a tolerable data demand for the preliminary search over the telescope area. So over the 2 year collection period this instrument will collect 11.2 GB of lunar surface data.

#### E.2.2.4. Electrometer

Scoping down to the less data intensive instruments, the electrometer will only require 3.7 KB of data per telescope arm. This equates to 11.1 KB over three arms and a total of 999 KB for the whole telescope area. Because of its low data demands, the electrometer will be able to map the area before the telescope is deployed. Over the 2 year period the electrometer will only collect 999 KB of data.

#### E.2.2.5. Seismometer

For the seismometers, the data quantities over the two year period are relatively low. The total amount of seismic data collected over a 2 year period comes out to be 4.3 MB. This is assuming the use of 3 seismometers (1 per arm). Each seismometer is able to collect 24 bit samples (waves). Assuming that a quake on the moon will produce an average of 150 waves over a 10 minute period, a seismometer can collect a total of 450 bytes of data per quake. With the average number of quakes on the Moon being 3,200 a year (insert source), one seismometer will be able to collect a total of 1.44 MB of seismic data a year with a total of 2.88 MB over a two year period. Since the data demands are very light for this instrument it will be able to operate simultaneously with the telescope without any storage issues.

**Table 3. Data summary over mission duration**

| Instrument | Total Data (Over 2 years) | |
|---|---|---|
| | **Baseline** | **Threshold** |
| Telescope | 68.3 TB Max. | 34.2 TB Max. |
| CRUX GPR | >711 GB | >711 GB |
| PRM Fluxgate Magnetometer | 11.2 GB | 11.2 GB |
| MECA Electrometer | 999 KB | 999 KB |
| ExoMars Seismometer | 2.88 MB | 2.88 MB |

#### E.2.2.6. Issue with Data Collection

With collecting data for this mission, there are some issues that may arise. Since the Moon experiences an average of 3,200 quakes a year (27), quakes may affect the way the dipole units collect radio emission data. Since the mission will be implementing seismometers to measure seismic activity, comparing the radio data collected by the telescope with the seismic data will give an idea as to how the radio data was affected. Another factor that could occur in the collection of the radio data is interference due to the electrical and magnetic properties of the lunar soil. Depending on how strong these properties of the soil are, it could interfere with the VLF signals and how the telescope is reading those signals. As with the seismometers, the electric and magnetic data collected from the magnetometers and electrometers will give insight into the effects the soil will have on the data retrieved from the telescopes.

Other than the radio data, there could be issues that arise with the collection in the GPRs, magnetometers and electrometers. Since, these instruments will be collecting data on the deployment rovers as the rovers are moving, issues can arise based on the speed of the rovers. If the rovers are traveling too fast, then the instruments may not pick up correct or high resolution data. To ensure that these issues do not occur, the instruments will have to be tested at various rover speeds to see which speed gives the best results.

## E.3. Science Mission Profile

During the science mission, a lot of events will occur to ensure that data is being collected and transmitted properly for the success of the mission. Factors that determine this success will be the parameters set by the mission and how they relate to the science objectives, the orbit of the orbiters, observing periods, data transmission periods and time critical events. The following subsections below will layout a profile of all of these factors.

### *E.3.1. Mission-Relevant Parameters*

For this mission, a set of measurement requirements have been made in order to accomplish the proposed science objectives of this mission. Table X, presents the relationship between the proposed science objectives, the selected instruments and the measurement requirements in order for these instruments to accomplish the science objectives.

### *E.3.2. Orbit*

The orbit being implemented for either a baseline of 2 orbiters or a threshold of 1 orbiter, will be a 100 km periapsis and a 1000 km apoapsis. These orbital parameters will form an elliptical orbit around the Moon with the apoapsis being on the far side and the periapsis being on the near side.

### *E.3.3. Data Transmission and Techniques*

Over the course of collecting data, the mission will implement a baseline of two orbiters and a threshold of one orbiter for data transmissions from the Moon to the orbiter and from the orbiter to Earth. With the implementation of two orbiters for the baseline, the radio telescope will be transmitting data to the orbiters 18 times each day with an uplink time of 2,000 seconds per pass. With the communications between the orbiter and the telescope being 100 Mbps, a maximum of 25 GB will be collected per pass with a maximum daily total of 450 GB. With a threshold of one orbiter making 9 passes a day the total daily collection comes out to be a maximum of 225 GB per day. The combination of the number of passes and the daily maximum data collections, the data transmission methods will suffice for maximizing the amount of data being collected for this mission.

### *E.3.4. Time Critical Events*

There are a few time critical events that must be taken into consideration for this mission. These events include being able to look at the interstellar medium and the Sun long enough to collect data about a particular event as well as what occurs when transmitting data back to the orbiters.

When pointing at an object such as the interstellar medium, the telescope will be pretty much pointing at the sky. In this case, there will not be much concern about looking long enough at this object, since the telescope will be viewing it most of the time. In the case of the Sun, the telescope has a two week period each month to collect high energy particle acceleration data. Because the duration of the mission will occur during a solar minimum, this time period to view an event on the Sun may not be long enough in some instances and because of this it is a time critical factor for the telescope to be active and collecting during every two week period.

Transmitting data is a time critical event that must happen at the right time during the right pass. When the on board storage of the lander has been filled, the telescope and seismometers will stop the data collection process and begin transmitting data back to the orbiters. Once all of the data in the on board storage has been transmitted, the telescope and seismometers will resume operation. This process must be planned out accordingly and accurately to ensure that down time for the telescope is minimal, because every minute the telescope is not collecting is 2 MB of data lost.

## E.4. Data Plan

Retrieving and analyzing the data collected from the two year collection period is a crucial part to the science of this mission. Initially all data retrieved from the telescope will be Level 0 data. No processing of the data will be done on the telescope, since power requirements and mass are limited. Once the data has been retrieved by ground communications, it will be sent to a correlation center for transformation into Level 1 data. After more processing, the final results will be Level 2 data which will be archived with the Level 0 and 1 data. The following subsections will describe in more detail the data retrieval process, validation and calibration, and data archiving.

### *E.4.1. Data Retrieval*

With the telescope being permanently placed on the far side of the Moon within the Daedalus crater, data retrieval will occur whenever a radio event from an object occurs. Data retrieval of lunar data will occur before the deployment of the telescope as well as in between telescope operations. All data collected will be Level 0 data. To handle all of the data coming into the lander, the lander will be equipped with a DPU, in order to handle all of the instruments. This DPU will be the Sandia SA3300 which has heritage from the WAVES experiment (23). It will serve the purpose of controlling and acquiring data from the crossed dipole units, the CRUX GPR, the Fluxgate Magnetometers, the MECA Electrometers and the ExoMars seismometers. The DPU will also serve the purpose of handling the communications of the acquired data to the orbiters and handling software and diagnostic processes of the lander. The DPU on the WAVES experiment spacecraft was only designed to handle 8 different instruments and sensors (23). Because of this, the DPU for this mission will have to be modified to support 130 dipole units and at least 4 different science instruments. The rationale behind choosing this DPU is because it was designed to handle radio emission data and because it provides power and simplicity of programming which will be an advantage in designing and programming the software needed for the mission. Once the DPU has acquired data from the instruments and has stored it in the lander's storage, it will then transmit the data back to an orbiter. Once the orbiters are within the view of the Earth, the data will be transmitted back to Earth via the DSN. Once on Earth the validation, calibration and processing of the data will occur.

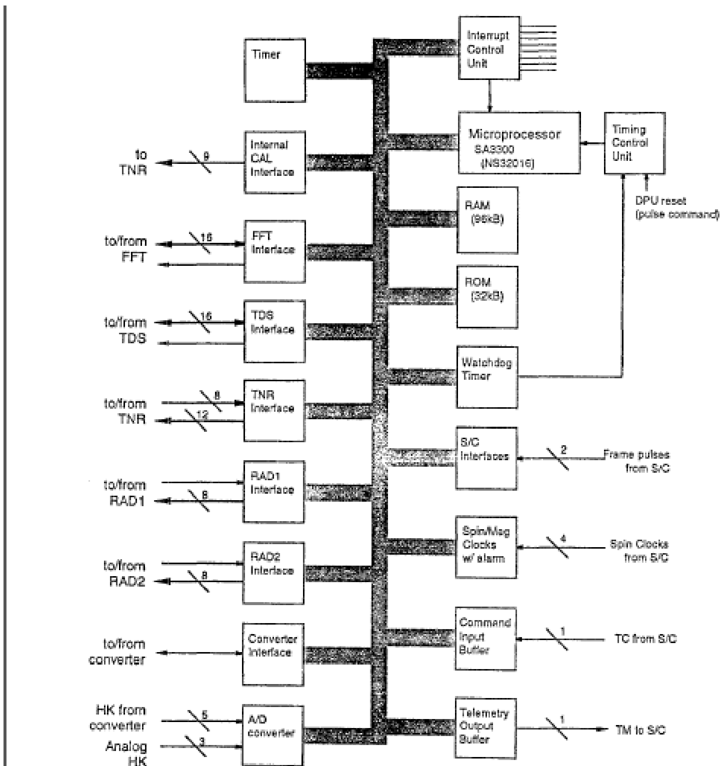

Fig. 7. The DPU microprocessor block diagram.

**Figure 5. Data retrieval**

### *E.4.2. Data Validation and Calibration*

During the data validation and calibration portion, the Level 0 data will be transformed into Level 1 data. This will be done using a correlator station very similar to EVLA-WIDAR (31). When the same event hits the telescope, different dipole units are collecting the same event and during the collection, these signals are not synced so they do not form a coherent image. By processing the data through a correlation center, these signals can be synced based on the times they came in by shifting the signals across the time axis until a signal matches another. Once all the signals have been matched the data will form coherent images of the interstellar medium as well as solar events.

After the radio data has been correlated, the lunar data will have to be analyzed as well. Once it is analyzed, this data will have to be correlated with the radio data to figure out relationships between the radio data and the effects the electromagnetic properties of soil and seismic events. From this stage the Level 1 and Level 2 data will be produced for the final product.

### *E.4.3. Data Archiving*

When the Level 0 data has been received and the final data products are produced, they will all be stored in two NASA funded databases. All of the radio telescope data will be stored in the National Space and Science Data Center (NSSDC) and all of the lunar environment data will be stored in the Planetary Data System (PDS). Within the first six months after data collection, level

0 data and possibly level 1 data will be stored into both of these data archives. Later on after the data has been fully analyzed by the science team, the Level 2 data will be stored. For storing the data in these data archives, the science team will format the data into the Common Data Format (CDF). This format was chosen because it is accepted by the PDS, has a self describing XML based format where meta data can be used to describe the data, it is easy for computer programmers and applications to manipulate the data, and because it supports large files (> 2 GB) (28).

After the data has been processed, analyzed and formatted properly, the science team will have to specify how much storage will be needed for the data.  For the lunar environment data, the science team will have to allocate at maximum of 1.08 TB of data for the PDS. This includes 722.2 GB of raw data and 361.1 GB of scientific data. For the radio data, the science team will have to allocate a total of 4.05 PB of storage for the NSSDC. This storage will include the 2.7 PB of raw data collected and assuming that half the data turns out to be translatable into scientific data, 1.35 PB of scientific data. The data threshold storage threshold for NSSDC will be 2.03 PB.

When all the data has been analyzed by the science team, the final scientific data product will be VLF images of the interstellar medium and high particle acceleration events on the Sun. What will separate this data from other VLF data is that it will be untouched by terrestrial RFI and VLF enhancement equipment. This data will provide a new look into the VLF realm of our galaxy.

### E.5. Science Team

This section identifies the members of the RAM science team as well as descriptions about their roles and responsibilities in this mission. The salaries and funding for these members directly comes out of the mission's budget.

**Philip Meyer** (PI) is currently a Physics student at the College of Charleston who is serving as the principal investigator of this mission. As the principal investigator, Philip is responsible for leading and making the final decisions for the science team. To accomplish this, he must keep in constant contact with his Co-I for information on the science investigation and implementation as well as to make sure the Co-I is on task with all assigned work. He also has to make sure that deadlines of the project are met and that the science investigation and implementation are clear to the PM and CE of the RAM engineering team. For more information about Philip's experience and education, his resume can be referenced in section J.3.

**Jesse Snider** (Co-I) is a student of Computer Science at the College of Charleston and is currently serving as the co-investigator of this mission. As the co-investigator, Jesse is responsible for completing any tasks assigned by the PI and to assist the PI in researching and defining the science investigation and science implementation portions of the RAM mission. Jesse does sit in on teleconferencing calls between the PM and the PI in order to be up to date with the status of the mission as well as place his input when necessary or ask questions. For more information on Jesse's experience, his resume can be referenced in section J.3.

### E.6. Plan for Science Enhancement Option (SEO)

This mission does not have a plan for an SEO option in this proposal.

## F. Mission Implementation

### F.1. General Requirements and Mission Traceability

The goal of the mission proposed in this report is to accommodate the science objectives outlined in Sections D and E. The science objectives require that the Flight Vehicle accommodate the science equipment along with the other equipment necessary to achieve the science objectives and to operate for one year to accomplish the baseline science objectives. LI was given two Launch Vehicle (LV) options for this mission. The options were a single Delta IV Heavy or two Atlas V 551s. In order to accommodate the large mass requirements for this mission, the two Atlas V 551s were selected over the single Delta IV Heavy LV option. Furthermore, if both Flight Vehicles successfully make it to the far side of the moon, the two Atlas V 551 LVs provide redundancies since both Flight Vehicles have identical payloads: a Lander, an Orbiter, and a mobility system named Mini-All-Terrain Hex-Limbed Extra-Terrestrial Explorer (MATHLETE). See Section F.2 for the Flight Vehicle configuration.

Additionally, each Flight Vehicle has propulsion systems that were designed to maximize the amount of mass that can be landed on the lunar surface. The baseline science objectives require placing 100 Lunar Radio Telescopes (LRT) in the Daedalus crater on the far side of the moon. LI decided to include an additional 15 LRTs per Lander, a total of 30 extra telescopes, to account for LRTs being incorrectly placed and/or failing over the lifespan of the mission. LI decided on an extra 15 LRTs per Lander based on the amount of available science payload mass on each Lander. The deployment of the 130 LRTs will be a "Y" shaped array in the eastern portion of the Daedalus crater because this region is relatively flat. Each MATHLETE will carry 65 LRTs from each Lander, positioning 43 telescopes on each arm of the "Y" and one telescope in the center. Since the LRTs and other science equipment will receive and transmit a large amount of data, another science requirement is to maximize the amount of communication time with the Orbiters. To accommodate this data requirement, each Orbiter will sustain a 1000-km apoapsis and 100-km periapsis orbit; see Section F.2.1.3. for orbit details. In sustaining this orbit, LI achieved a communication time between the two Orbiters and the science equipment in the Daedalus crater for approximately 261 days per year. The traceability of the science requirements to the Mission Functional, Mission Design, Spacecraft, Ground Systems and Operations Requirements can be seen in the Mission Traceability Matrix (Table 4).

As previously mentioned, each Atlas V 551 LV will contain identical payloads. With a single Flight Vehicle, the threshold science objectives can still be accomplished; however to accomplish the baseline science objectives, both Flight Vehicles are required.

## Table 4. Mission Traceability Matrix

| Mission Functional Requirements | Mission Design Requirements | Spacecraft Requirements | Ground System Requirements | Operation Requirements |
|---|---|---|---|---|
| Must attain LEO | Launch on Atlas V 551 Launch Vehicle | Mass: 6,524 kg (defined by C3 of -1.85) | Same as for any Atlas Launch Vehicle | Flight Vehicle in storage mode - monitor vibrations |
| Must fit into Atlas launch storage mode to deployed mode | Must use Atlas Adapter Must ship to Florida | Must fit Atlas Adapter Must account for shipping size and packing constraints | Logistics: If Flight Vehicle parts are shipped separate they must be combined in Florida before mounting on Atlas - may need storage space as well | Space components must align and mate properly to achieve a storage mode configuration |
| Flight Vehicle must go from launch storage mode to deployed mode | Flight Vehicle separates from Upper stage of Launch Vehicle | F must leave Atlas, discard unneeded launch equipment, and deploy necessary mechanical equipment like solar arrays | Atlas reception/retrieval<br>Observe and confirm successful deployment | Use thrusters to establish orbit Mechanical deployment will be automated by diagnostic feedback |
| Travel to the Moon | Perform Earth to Moon propulsive maneuvers | Engine and fuel to achieve $\Delta V$ must survive transit environment | Monitor Flight Vehicle travel and make adjustments as necessary | Single long burn to establish trajectory and rotate to distribute heat evenly throughout the Flight Vehicle |
| Orbit the Moon | Flight Vehicle will orbit the Moon and have ALHAT scan the surface. | Engine and fuel to achieve $\Delta V$ must survive transit environment | Monitor Flight Vehicle travel and make adjustments as necessary | Orbit the Moon enough times to meet ALHAT's requirements for landing. |
| Lander and Orbiter separation | Lander and Orbiter will separate | Lander and Orbiter shall be capable of successfully separating without causing damage to either system | Submit command to Orbiter and Lander to separate once ALHAT has gathered enough data. | Lander and Orbiter must separate |
| Orbiter will attain elliptical lunar orbit | Orbiter will attain elliptical lunar orbit of 1000-km apoapsis and 100-km periapsis | Orbiter shall have an engine and fuel capable of performing necessary propulsive maneuver for elliptical orbit | Monitor Orbiter and make adjustments to trajectory as necessary | Orbiter relays information from science and mission equipment on the far side of the moon to Earth |
| Lander shall land in the Daedalus crater | ALHAT calculates and controls Lander's systems to safely land | Lander shall be able to properly power ALHAT and have adequate fuel and propulsive capabilities to land | None – ALHAT is completely autonomous | Safely land in the Daedalus crater |
| Placement of Radio Telescopes in Daedalus crater | Radio telescopes must be placed in "Y" shaped array with the furthest tips of the array being 30-km apart | MATHLETE shall be capable of traversing lunar surface in the Daedalus crater and safely place telescopes | Monitor placement of telescopes and make corrections as necessary | MATHLETE shall place telescopes approximately 0.54 km apart |
| Science Wheel to record data around Radio Telescopes | Mobility System must slow down to 0.6km/hr before placing Radio Telescope | MATHLETE shall be capable of lowering speed 100-m before placing Radio Telescope and provide 1.106 W of power | Monitor placement of telescopes and make corrections as necessary | Investigate seismic activity on the moon that results from moon quakes and impacts and the electromagnetic properties of the lunar surface. |
| Ground Penetrating Radar collect data | Operate only when Radio Telescopes are not observing the Sun or a celestial body | MATHLETE shall be capable of housing Ground Penetrating Power and providing 1 W for GPR operations and shall move the Radio Telescope array area. | Monitor Radio Telescope activity and give the command for the GPR to active and for MATHLETE to traverse the entire Radio Telescope array area. | Investigate the lunar geological subsurface structure. |

## F.2. Mission Concept Descriptions

This mission begins when the first of two Atlas V 551 LVs is launched from Cape Canaveral. Each launch vehicle will contain the exact same payload; the redundancy mitigates the risk of the mission. The second LV will be launched approximately one month after the initial launch. En route to the Moon, there are several burns that have to take place in order to fulfill ALHAT requirements; these burns can be seen in Figures 6 and are further detailed in Table 7 and Section F.2.3.1. After both Landers are on the surface of the Moon, the MATHLETEs will deploy the LRTs. Once the LRTs are properly deployed, with the exact locations determined by pinging each telescope from the Lander. Each telescope will be capable of transmitting the data to both Landers. Both Landers will transmit the compiled and compressed information to the Orbiters. The Orbiters will store the information until able to transmit it back to the ground stations on Earth. Using two Orbiters with equatorial elliptical orbits described in Figure 8, the coverage will be approximately 261 days out of the year. This mission will continue for up to 4 years to gather needed information. Figure 6 is a visual representation of the concept of operations for the mission. Figure 7 is a visual breakdown of the Flight Vehicle.

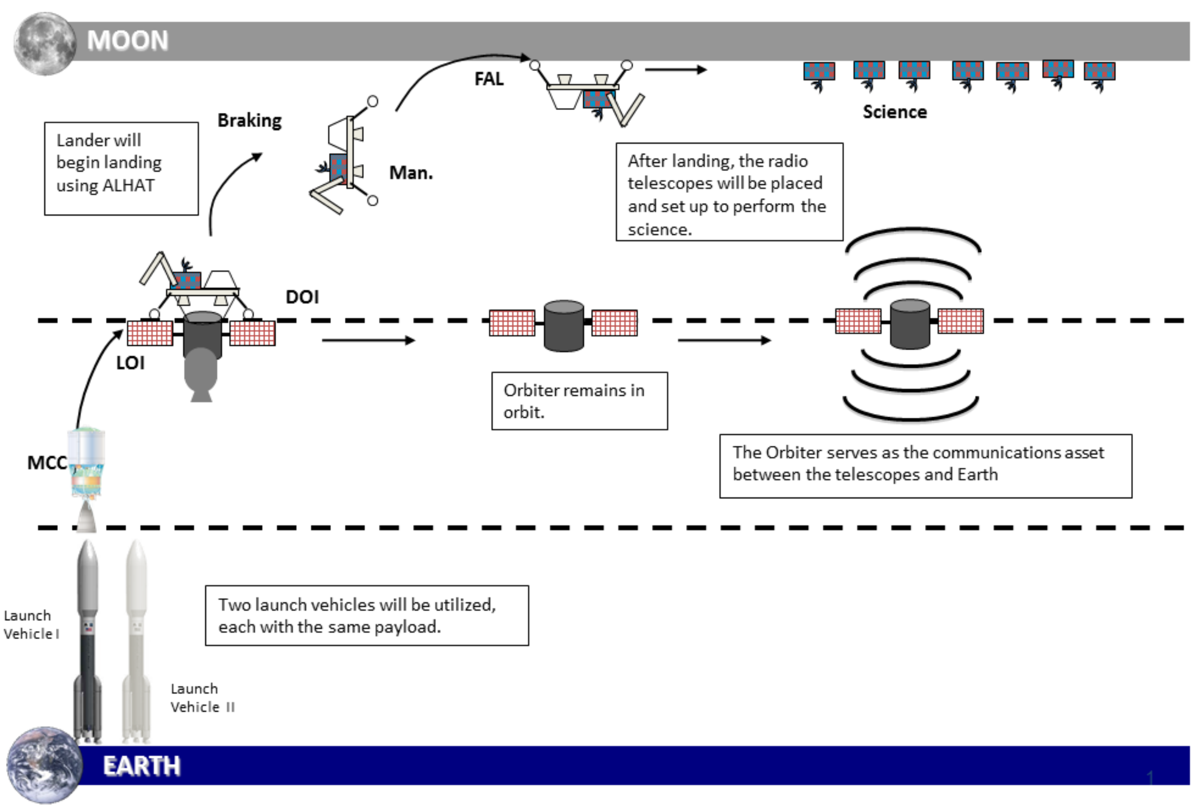


**Figure 6. Concept of Operations (12)**

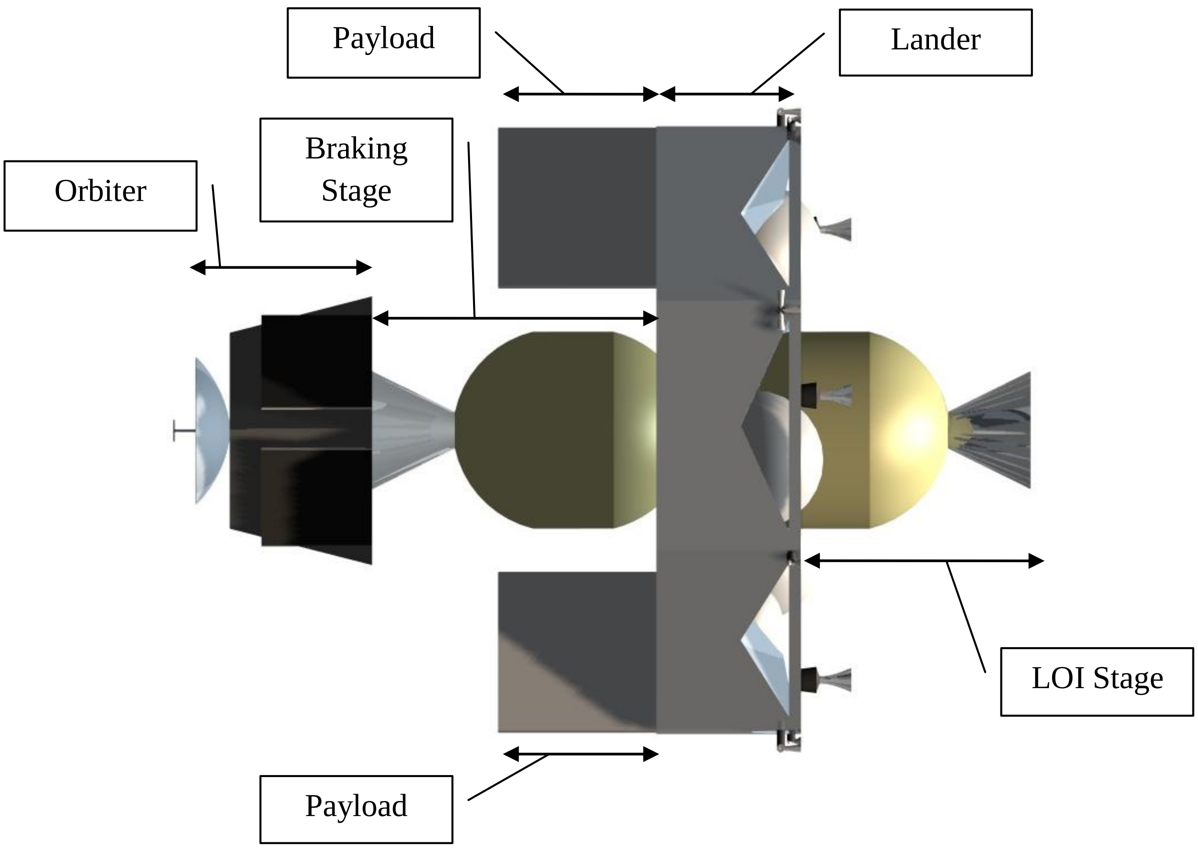


**Figure 7. Flight Vehicle Stack.**

## *F.2.1. Mission Design*

### F.2.1.1. Launch Date

The first Atlas V 551 LV will launch on 4 November 2017. The second Atlas V 551 LV will launch on 4 December 2017.

### F.2.1.2. Duration

Flight Vehicle 1 will depart on 4 November 2017, 11:52:00 GMT, and will perform the mid-course correction (MCC) in order to most efficiently reach the Moon. On 4 November 2017, 12:30:17 GMT, the trans lunar injection (TLI) will be performed by the upper stage of the LV. In order to enter a stable orbit of the moon, the lunar orbit insertion (LOI) will be performed on 7 November 2017, 16:45:10 GMT. On 8 November 2017, 09:06:15 GMT, Flight Vehicle 1 will initiate the deorbit initiation (DOI) and braking burn (Brake). (12)

Flight Vehicle 2 will depart at 4 December 2017, 13:33:20 GMT, and will perform the MCC in order to most efficiently reach the Moon. On 4 December 2017, 14:08:36 GMT, the TLI will be performed by the upper stage of the LV. In order to enter a stable orbit of the moon, the LOI will be performed on 7 December 2017, 21:57:20 GMT. On 7 December 2017, 21:57:20 GMT, Flight Vehicle 2 will initiate the DOI and Brake. (12) These propulsive maneuvers will be further discussed in F.2.3.

The mission duration is described in Table 5.

**Table 5. Mission Duration (12)**

| | | | | | |
|---|---|---|---|---|---|
| Phase E | Total | | 2year 6month | 4th Nov. 2017, 11:52:00 GMT | May.2020 |
| | The Spacecraft 1 | **Total** | 4day5hr4min22sec | 4th Nov. 2017, 11:52:00 GMT | 8th Nov. 2017, 16:56:22 GMT |
| | | MCC | 3day4hr53min10sec | 4th Nov. 2017, 11:52:00 GMT | 7th Nov. 2017, 16:45:10 GMT |
| | | LOI | 1min25sec | 7th Nov. 2017, 16:45:10 GMT | 7th Nov. 2017, 16:46:35 GMT |
| | | On orbit | 1day | 7th Nov. 2017, 16:46:35 GMT | 8th Nov. 2017, 16:46:35 GMT |
| | | DOI | 1sec | 8th Nov. 2017, 16:46:35 GMT | 8th Nov. 2017, 16:46:36 GMT |
| | | Brake | 1min25sec | 8th Nov. 2017, 16:46:36 GMT | 8th Nov. 2017, 16:48:01 GMT |
| | | Man | 1sec | 8th Nov. 2017, 16:48:01 GMT | 8th Nov. 2017, 16:48:02 GMT |
| | | FAL | 8min20sec | 8th Nov. 2017, 16:48:02 GMT | 8th Nov. 2017, 16:56:22 GMT |
| | The Spacecraft 2 | **Total** | 4day8hr35min12sec | 4th Nov. 2017, 13:33:20 GMT | 8th Nov. 2017, 22:08:32 GMT |
| | | MCC | 3day8hr24min | 4th Nov. 2017, 13:33:20 GMT | 7th Nov. 2017, 21:57:20 GMT |
| | | LOI | 1min25sec | 7th Nov. 2017, 21:57:20 GMT | 7th Nov. 2017, 21:58:45 GMT |
| | | On orbit | 1day | 7th Nov. 2017, 21:58:45 GMT | 8th Nov. 2017, 21:58:45 GMT |
| | | DOI | 1sec | 8th Nov. 2017, 21:58:45 GMT | 8th Nov. 2017, 21:58:46 GMT |
| | | Brake | 1min25sec | 8th Nov. 2017, 21:58:46 GMT | 8th Nov. 2017, 22:00:11 GMT |
| | | Man | 1sec | 8th Nov. 2017, 22:00:11 GMT | 8th Nov. 2017, 22:00:12 GMT |
| | | FAL | 8min20sec | 8th Nov. 2017, 22:00:12 GMT | 8th Nov. 2017, 22:08:32 GMT |
| | Science | | 2year 6month | 8th Nov. 2017, 22:08:32 GMT | May.2020 |
| Phase F | | | 1 month | May.2020 | Jun. 2020 |

### F.2.1.3. Orbital Details

The trajectory to the moon will be defined with a C3 of -1.85.(12) This C3 creates a slow approach to the moon, but increases the overall throw mass. Since this is an unmanned robotic mission, the increase in throw mass of the launch vehicle is more beneficial than arriving at the moon sooner.

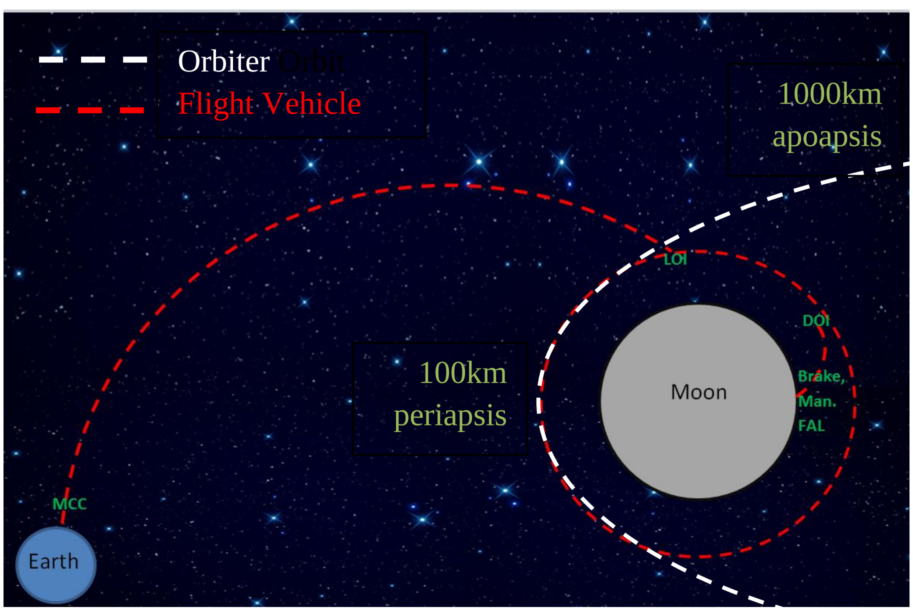


**Figure 8. Trajectory of Flight Vehicle and Orbiter**

#### F.2.1.4. Critical Events

The critical events for this mission are listed in Table 6. Each event is graphically depicted in the Concept of Operations in Figure 6. A critical event is defined as a distinct event within the mission operations which if not performed successfully would result in a failed mission.

**Table 6. Critical Events and Descriptions**

| **Critical Event** | **Description** |
|---|---|
| Launch of Atlas V 551 LV | Each LV must successfully launch and push the flight vehicle towards the moon in order to accomplish mission objectives on far side of moon. |
| **Propulsive Maneuvers** | |
| MCC | ACS thrusters and engines on the Lander must successfully complete the MCC as necessary in order to ensure that flight vehicle is put on a trajectory that will reach the moon. |
| LOI | The LOI stage must successfully complete the LOI burn. |
| DOI | The Lander must successfully complete the DOI burn. |
| Braking Burn | The Braking stage must successfully complete the DOI burn. |
| ALHAT Landing on Lunar Surface | ALHAT must avoid hazards while landing autonomously on the lunar surface. |
| **Lunar Surface Operations** | |
| LRT Deployment | MATHLETE must lay out the LRTs in the correct orientation on the lunar surface for LRTs to function properly. |
| MATHLETE Operations | MATHLETE must successfully traverse the lunar surface. |
| Communication from Equipment to Lander | The equipment on the far side of the moon must successfully communicate with the Lander. |
| Communication from Lander to Orbiter | The Lander must successfully communicate data gathered from equipment on the far side of the moon and communicate it to the Orbiter. |
| Communication from Orbiter to Earth | All data received from the Orbiter must be successfully communicated back to Earth where it can be archived and processed. |

### *F.2.2. Launch Vehicle Compatibility*

The Flight Vehicle chosen to be in orbit and on mission to the moon is the Atlas V 551. This launch vehicle is operated by the United Launch Alliance (ULA). An Atlas V Launch Services User's Guide (AVUG) is prepared by the ULA to prepare groups who will use the Atlas V. The launch site will be the launch pad in Cape Canaveral during the time frame of December 2017 to December 2022. (15)

#### F.2.2.1. Mass Constraints

The mass constraint on the mission is determined by the throw mass of the launch vehicle. The throw mass used is a function of the launch trajectory and the launch vehicle. The throw mass for an Atlas V 551 using a C3 of -1.85 is determined to be 6524 kg. (15)

#### F.2.2.2. Payload Faring (PLF) (Volume Constraints)

The volume constraints are determined by using the geometry and the measurements of the short faring. The allowable volume in the faring was determined to be 306.57 $m^3$. The maximum height of the Flight Vehicle is 20.7 m. The maximum width of the Flight Vehicle was found to be 4.57 m. (15)

#### F.2.2.3. Adapter Selection

A machined aluminum structure in a monocoque cylinder form is known as an adapter or a C-adapter. The standard adapter chosen for the Atlas V 551 is a Type B1194 adapter which will be provided by NASA. This adapter may have up to five configurations for the Payload Separation Ring (PSR), with the C22 adapter being the first option. The mass of the C22 Adapter and the PSR is 84.4 kg. The Type B1194 payload adapter consists of two major sections: the payload separation ring and the LV adapter. The PSR is an aluminum component in the shape of a truncated cone. The cone shape consists of a forward ring and an aft ring. The LV adapter and the aft ring are joined together by 120 evenly spaced bolts. This adapter also consist of a symmetrical bolt hole pattern to allow the PSR and the Structural Capabilities (SC) to be rotated in three degree increments relative to the launch vehicle. The PSR supports all hardware that directly relates to the SC. (15)

### *F.2.3. Flight System Capabilities*

#### F.2.3.1. Flight Vehicle Staging

The Flight Vehicle staging was designed initially only to provide the most usable mass on the surface. Many different configurations and engine types were tested using the Tsiolkovsky equation and Propellant Mass Fraction method. The final configuration can be seen in Figure 7.

After the LV pushes the Flight Vehicle toward the moon, the MCC will be performed by the attitude control system (ACS) thrusters on the Lander to correct the current trajectory. When the Flight Vehicle reaches a 100km circular orbit around the moon, a LOI will be performed by a Star 48 V solid rocket motor (SRM); after the LOI is performed, the SRM and the Orbiter will separate from the remaining stages. The Orbiter will then perform a small burn to enter a new 1000 km apoapsis/100 km periapsis elliptical orbit. The remaining stages will continue to orbit the Moon for one day, allowing ALHAT to acquire the needed surface information. Once ALHAT has sufficient information, a DOI will be performed by the main thrusters of the Lander. At the correct time, a Brake will be performed by another Star 48 V SRM. After the Brake, the SRM will separate from the Lander, which will continue toward the surface of the Moon. The Lander will then perform a corrective maneuver (Man.) burn if required by ALHAT in order to avoid an obstacle. When ALHAT commands, the Lander will perform the final approach and landing (FAL) burn that places the Lander on the lunar surface. Sections F.2.3.1.1 and F.2.3.2.2 further detail the propulsive elements of the Flight Vehicle. (10)

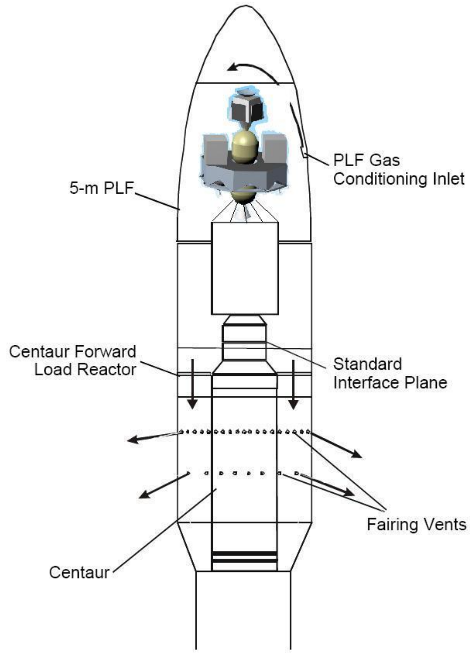


**Figure 9. Flight Vehicle in Faring.**

*F.2.3.1.1. Propulsion*

The propulsion for the Flight Vehicle is divided into two parts: the solid propellant engine stages and the monopropellant engines that are on the Lander. The monopropellant engine stages are discussed in Section F.2.3.2.2. Both solid propellant engine stages are Star 48 V engines. Stage I, the LOI stage, has zero offload. Stage II, the Brake stage, has 7% offload. By using the same engine design, it reduces the cost of buying two solid propellant engines. An overview of the specifications for the engine is in Table 7. $_{(13)}$

**Table 7. Solid Propellant Engine Specifications $_{(13)}$**

| Engine | Propellant Type | $I_{sp}$ (s) | Mass, Engine Only (kg) | Thrust (N) | Max Power Required (W) | Inlet Pressure (bar) |
|---|---|---|---|---|---|---|
| Star 48 V | Solid Propellant | 292.1 | 116 | 68636 | 100 | 39.9 |

*F.2.3.1.2. Thermal System*

The chosen propulsion design has two SRM stages. Each SRM will have 10 layers of Multi-Layer Insulation (MLI) and will rotate at 6 rpm. The dimensions of the thermal system were designed using a cube with a length of 4.25 m, a width of 4.25 m, and a height of 2 m as the model. Thermal systems for the Flight Vehicle will be discussed further in Section F.2.3.2.6. $_{(10)}$

### F.2.3.2. Lander

The Lander for this mission has two primary purposes: the first being to safely land the science equipment and the MATHLETE on the lunar surface and the second being to act as the primary communication between the LRTs and the Orbiter.  Additionally, the Lander will house the

InSPIRESS Level 1 high school experiment proposed by Sparkman High School. This will include voltmeter sensors on the feet of the Lander and four small cylinders that will be used to launch science devices approximately 10 m from the Lander.

*F.2.3.2.1. Mass Breakdown*

The allocation of mass throughout the systems of the Lander was based on historical missions with similar lander objectives to land on the Moon. The mass allocated to each portion of the Lander also included 30% contingency for growth.

**Table 8. Lander Dry Mass Breakdown (9)**

| Subsystem | Allocated Mass (kg) |
|---|---|
| Payload | 548.31 |
| Mechanical | 495.73 |
| Propulsion | 114.41 |
| Power | 80.73 |
| GN&C | 3.26 |
| Thermal | 10.32 |
| Communications | 1.63 |
| Harness | 19.84 |
| **Total** | **1,274.23** |

*F.2.3.2.2. Propulsion*

The engines located on the Lander are all monopropellant engines, the specifications of which are in Table 9. The MR-80B engines are the main engines that provide the majority of the thrust for the Lander during the FAL and DOI. The engine was chosen for its large maximum thrust and its ability to throttle the thrust to approximately 1% of the maximum thrust. The MR-106L engines are the ACS engines for the Lander. The MR-106L was chosen because of its small mass and power requirements, as well as its ability to burn for several thousand seconds, which is important while performing the MCC. The MR-107M engines are additional engines that help the ACS engines to perform the MCC and provide any extra thrust needed. They were chosen because of their small mass and power requirements and large thrust capabilities. (13)

**Table 9. Monopropellant Engines Specifications (13)**

| Engine | $I_{sp}$ (s) | Mass, Engine Only (kg) | Thrust (N) | Max Power Required (W) | Inlet Pressure (bar) |
|---|---|---|---|---|---|
| MR-80B | 220 | 7.94 | 3100 | 183 | 36.9 |
| MR-107M | 225 | 0.9 | 220 | 37 | 29.7 |
| MR-106L | 230 | 0.59 | 22 | 41.7 | 27.6 |

*F.2.3.2.3. Command and Data Handling (C&DH)*

Upon reaching the lunar surface, the lander will be the command headquarters for the mission. A RAD 750 will be used to take care of all C&DH needs on the Lander. The Orbiter will receive commands from Earth using Ka-band frequency and transmit these commands to the Lander using X-band frequency. The ultra high frequency (UHF) transceiver on the Lander will then communicate these commands to the science equipment and the MATHLETE. (20) (2) (1)

Additionally the Lander will be taking in data from all equipment on the lunar surface and temporarily storing it until able to communicate with the Orbiter.

*F.2.3.2.4. Power Requirements*

The Lander will be the primary data handling center on the lunar surface. In order to power all of the devices on board the Lander, a combination of primary and secondary batteries will be used. ALHAT and the high school science experiment will both run on primary batteries; ALHAT for 8.5 minutes and the high school experiment for 28 days. The UHF transceiver, X-band transceiver, RAD 750, antenna, and thermal systems will all run off the secondary batteries. Because of power constraints, certain power systems will only be able to operate for approximately 44% of the night cycle, the total night cycle being approximately 336 hours. See Table 10 for power system requirements. The mass requirements for these batteries have been summarized in Table 11. Refer to Section J.14.4 for more detailed analysis of the power system requirements.

**Table 10. Lander Power System**

| **Primary Batteries** | | | |
|---|---|---|---|
| **Device** | **Power (W)** | **Time (hr)** | **W-hr** |
| ALHAT | 260 | 0.14 | 36.8 |
| Voltmeter (High School) | 1 | 672 | 672 |
| | | **Total W-hr** | **708.8** |
| **Secondary Batteries** | | | |
| **Device** | **Power (W)** | **Time (hr)** | **W-hr** |
| UHF Transceiver | 15 | 147.8 | 2217.6 |
| X-band Transceiver | 15 | 150 | 900 |
| RAD 750 | 6 | 100.8 | 1512 |
| Antenna | 15 | 150 | 2250 |
| Thermal | 10 | 336 | 3360 |
| | | **Total W-hr** | **10239.6** |

**Table 11. Power System Mass**

| **Power Element** | **Mass (kg)** |
|---|---|
| Primary Battery | 2.29 |
| Secondary Battery | 93.1 |
| Solar Panel | 0.25 |
| **Total Mass** | **95.64** |

*F.2.3.2.5. Guidance, Navigation, and Control (GN&C)*

The GN&C of the Lander will be performed by ALHAT. After the Lander has made its initial orientation orbits around the Moon, ALHAT will have collected all of the necessary topographical data of the Daedalus crater. ALHAT will then perform the critical maneuvers before the FAL. As the Lander approaches the Daedalus crater, ALHAT will continue to maintain course and will make all corrections necessary to achieve a successful landing. (19)

#### *F.2.3.2.6. Thermal System*

The environmental assumption while designing the thermal system was that the temperature in the Daedalus crater will range from 100 K to 400 K.

As the Flight Vehicle approaches the Moon, the radiation values will increase. MLI and reflective paint will ensure proper cooling and insulation of the Flight Vehicle. A 10 layer Teflon MLI coating will be used to coat the entire Flight Vehicle. A series of louvers located at the perimeter of the Flight Vehicle will allow radiation and dissipation of heat. The rate of heat flow is controlled by opening and closing the louver blades. (10)

Additionally, the radiator's size is dependent on the solar heat flux and the heat dissipation. The maximum heat dissipation calculated is 260 W, which is for extreme cases. Along with heat dissipation, solar radiation contributes to the thermal control. (10)

Each electronic devise will be wrapped in MLI to maintain standard operating temperatures. The maximum allowable operating temperature will range from 288-300 K. This range accounts for the orbital electronics, batteries, and tools needed. (10)

### F.2.3.3. Mobility System (MATHLETE)

The mobility system was developed by the InSPIRESS Level 2 high school team comprised of students from Austin and Decatur High Schools. The mobility system that will be used for this mission will be a scaled down version of the All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE). The scaled down version of ATHLETE will be MATHLETE. MATHELETE was chosen for its ability to traverse rugged terrain using its six legged design. See Figure 10 for an image of ATHLETE. Although ATHLETE is an adequate mobility system, the design exceeds the mass and volume constraints of this mission. Because of this, a scaled down version, MATHLETE, was developed in order to retain the operational advantages of ATHLETE and still be within the mass and volume constraints. MATHLETE has been scaled down to approximately 10.7% of the original mass and size. See Table 12 below for comparison. (6)

**Figure 10. ATHLETE Mobility System (7)**

**Table 12. Comparison of ATHLETE and MATHLETE (6)**

| Specifications | ATHLETE | MATHLETE |
|---|---|---|
| Mass | 2,430 kg | 250 kg |
| Payload | 14,500 kg | 389 kg* |
| Length | 8.4 m | 0.9 m |
| Height(squatting) | 1.1 m | 0.12 m |
| Height | 6.4 m | 0.7 m |

*The payload was scaled down an additional 25% from the original 10.7%. This was done in order to be conservative in estimating the capabilities of MATHLETE.

MATHLETE will be used to place the LRTs, as mentioned in Section E.1. Additionally, MATHLETE will have four scientific devices on board which will analyze the lunar surface around the radio telescopes. The devices along with a description, mass and power requirements can be seen in Table 13.

**Table 13. Science Equipment onboard MATHLETE**

| Science Instrument | Science Objective | Mass (kg) | Power (W) |
|---|---|---|---|
| Magnetometer | Investigate the electromagnetic properties of the lunar surface. | 0.075 | 0.006 |
| Electrometer | | 0.05 | 0.1 |
| Seismometer | Investigate seismic activity on the moon that results from moon quakes and impacts. | 0.05 | 1 |
| Ground Penetrating Radar | Investigate the lunar geological subsurface structure. | 5 | 1 |
| | **Totals** | **5.175 kg** | **2.11 W** |

MATHLETE will use a gripper attachment designed by NASA to grasp the handle on the LRT and will then place the LRT on the lunar surface. See Figure 11 for an image of how the gripper is attached. (7)

**Figure 11. MATHLETE Gripper Attachment** (7)

*F.2.3.3.1. Power Requirements*

MATHLETE will require enough power to deploy the radio telescopes and conduct science experiments related to the geological properties of the lunar surface around the LRTs.

MATHLETE will be limited to operation time for only 44% of the time during the night cycle which is approximately 148 hours.  See to Table 14 below for the power system requirements and Table 15 for the mass requirements of the batteries. For further detail on power systems, refer to Section J.14.4.

**Table 14. MATHLETE Power Requirements**

| Device | Power (W) | Time (hr) | W-hr |
|---|---|---|---|
| Mobility System | 40 | 147.84 | 5913.60 |
| GN&C | 17 | 147.84 | 2513.28 |
| Avionics | 6 | 147.84 | 887.04 |
| Thermal | 10 | 336 | 3360 |
| RAD 750 (Data Handling) | 6 | 147.84 | 887.04 |
| Communications | 13 | 147.84 | 1921.92 |
| **Science Equipment** | | | |
| Magnetometer | 0.006 | 0.38 | 0.0023 |
| Electrometer | 0.1 | 0.38 | 0.038 |
| Seismometer | 1 | 0.38 | 0.38 |
| Ground Penetrating Radar | 1 | 84 | 84 |
| | | **Total W-hr** | **15567.29** |

**Table 15. Mass Requirements for MATHLETE Power Elements**

| Power Element | Mass (kg) |
|---|---|
| Secondary Battery | 141.52 |
| Solar Panel | 0.36 |
| **Total Mass** | **141.88** |

##### *F.2.3.3.2. Command and Data Handling (C&DH)*

MATHLETE will use an UHF transceiver to transmit the data from the science equipment aboard MATHLETE to the Lander. All data processing will be handled by a RAD 750. (20) (1)

##### *F.2.3.3.3. Guidance and Navigation (GN&C)*

The MATHLETE will have multiple cameras which will be used to create a 3D image of the lunar landscape.  This will allow MATHLETE to navigate the lunar surface. (8)

##### *F.2.3.3.4. Thermal System*

All scientific devices in the MATHLETE have self-sustaining thermal systems built into the devices.  All sensitive electronic devices in the MATHLETE will be housed in a Warm Electronics Box (WEB) which will also have a connection to a radiator to dissipate heat as needed. (9)

### *F.2.4. Additional Mission Elements*

#### F.2.4.1. Orbiter

The Orbiter will serve as the primary means of communication for this mission which will enable ground stations on Earth to collect data from the telescopes on the far side of the Moon. The Orbiter will also send mission commands to the Lander and MATHLETE. This orbiter is baptized LUNIV.

### *F.2.4.1.1. Subsystems*

The Orbiter consists of the five major subsystems shown in Table 16.

**Table 16. Subsystems Onboard Orbiter**

| Subsystems | Functions | Equipment |
|---|---|---|
| Attitude and Orbit Control System (AOCS) | Measures and corrects Flight Vehicle attitudes<br>Station-keeping | OSCAR Onboard Computer<br>Star trackers (reference sensors)<br>Gyroscopes ( inertial sensors)<br>Reaction wheels ( correction actuators) |
| Power Control System (PCS) | Manages power onboard supply.<br>Interface between power sources and payloads. | Array regulator<br>Battery control unit<br>Power distribution unit<br>Germanium cell solar arrays<br>4 Saft VES-180 Li-ion batteries |
| Thermal Control System (TCS) | Controls temperature inside the orbiter at 20°C | 350W mid-infrared tubes<br>Fins as cooling system<br>Multi-Layer Insulation (MLI) film |
| Data Handling System | Ensures data transmission and storage | Small Deep Space Transponder<br>1 TB SSD flash memories<br>Antenna |
| Propulsion System | Station-keeping<br>EOL maneuver | 10N bi-propellant thruster<br>(oxidizer)<br>MMH (fuel)<br>Mass of fuel (5 kg) |

### *F.2.4.1.2. Design*

LUNIV's chassis is made of aluminum tubes which have a 19 mm inner diameter and 25 mm outer diameter. These tubes are welded together. The Orbiter's shape is a "topless" pyramid with a 1.2 m x 1.2 m square bottom and a 0.9 m x 0.9 m square top. The height of the Orbiter is 0.9 m.

The "X" structure found on all surfaces except the top allows the Orbiter to withstand high G-forces while launching. LUNIV has two levels. The 10N bi-propellant thruster and the propellant are found on lower the level, while all other equipment is located on the upper level. Figure 12 depicts equipment location inside the Orbiter.

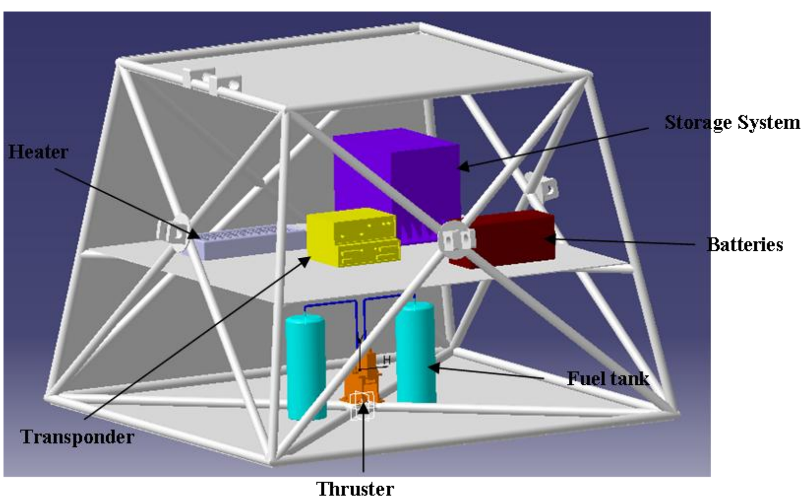


**Figure 12. Equipment Location Inside the Orbiter**

The solar arrays are connected to the Orbiter by pivot linkages. These linkages allow the panels to retract in order to fit inside the PLF while launching.  Once in space, the solar arrays are deployed. The Sun sensors detect the position of the Sun and orientate the solar arrays to face the Sun to generate the optimum power supply.

The Orbiter also has an antenna. Three pivot linkages along the three axes give the antenna abilities to turn and face any direction. Attitude and Orbit Control System (AOCS) will detect the position of the Earth and the moon allowing orientation of the parabola for optimum transfer. Figure 13 depicts the solar panels and antenna of the Orbiter.

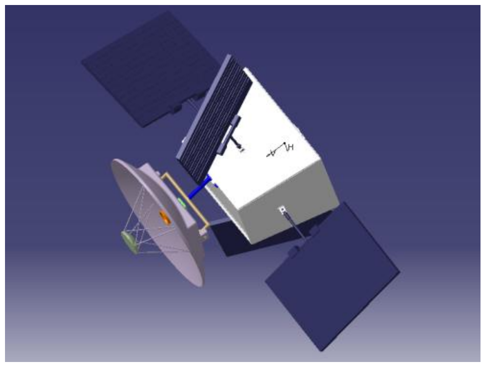

**Figure 13.  LUNIV**

### F.2.4.2. Cavitating Venturi Valve

The Throttling Cavitating Venturi Valve (TCaV) is a flow control valve that uses the cavitating effect, the formation of vapor bubbles of a flowing liquid in a region where the pressure of the liquid falls below its vapor pressure, to regulate the flow of propellant to the inlet of the engine. For our project we were given the task of redesigning an existing valve in a collaborative effort between Alabama A&M and UAHuntsville.  UAHuntsville's task was to design a lunar landing vehicle and the requirements for lunar landing and use the A&M designed TCaV as their main propellant valve. The current design of the valve is bulky, weighs 43 pounds, and is made of Monel k500 and 304L stainless steel materials. The overall goal of the redesign is to make the valve more flight ready by reducing the weight by at least 40% to help reduce the cost.

#### *F.2.4.2.1. Design*

Based on the engine requirements, the proposed valve configuration will provide a mass flow of hydrazine equal to 9.25lb/s (4.2 kg/s) at 300psia (inlet pressure).  The valve flow diameter is approximately 0.464in.  A lightweight body has been designed consisting of 304L stainless steel and monel.  Pressure loads have been analyzed to ensure structural integrity.  Combined loading (line loads + pressure) are still in work but the proposed design includes features that should mitigate any effects of these loads.  The gussets located on the valve body are incorporated to prevent failure from torque and bending.  Manufacturing and water flow testing are planned to verify flow capabilities. Refer to Section J.14.3 for design method and valve specifications.

### F.2.5. *Flight System Contingencies and Margin*

LI decided to design all flight elements with a 30% contingency. This was done by allocating each element with a portion of the total usable mass. The value of each portion allocated was then reduced by 30%. This reduced value was then set as each element's design mass. This gave each element the opportunity to grow by a contingency of 30% and at the same time keep the total mass of the flight vehicle below or equal to the total usable mass. As this mission was highly dependent on mass, no margin was designed into the usable mass. After an element was designed, excess mass from the allocation was then converted to margin that could be used by other elements.

### F.2.6. *Mission Operations*

#### F.2.6.1. Day/Night Cycle

During the night cycle (14 days, or 336 hours), all 130 LRTs are only active when facing the celestial body being observed. Based on science requirements the LRTs will be capable of being active up to 75% of the time (252 hours) in the night cycle. During the night cycle, all other science equipment will be able to operate up to 44% of the time. During the day cycle the LRTs will be observing the Sun and will be only active during solar events.

#### F.2.6.2. Lunar Surface Concept of Operations

Once both Landers have landed in the Daedalus crater, each MATHLETE will step off of its respective Lander. The MATHLETEs will then retrieve the containers of LRTs from its Lander. These containers will be placed on top of each MATHLETE. MATHLETE will then begin placing the LRTs in a "Y" shaped array. Each arm of the array will have 43 LRTs and will be approximately 17.3 km long, with a single LRT being in the center of the array. Each LRT will be placed approximately 0.4 km from each other in order to evenly space the LRTs. This spacing meets the science requirement of having the two LRTs approximately 30 km apart. The normal operating speed of MATHLETE will be 6 km/hr. When the MATHLETE arrives within 5 m of the next LRT deployment location, it will slow down to 0.06 km/hr and begin collecting data using the Science Wheel which includes the magnetometer, the electrometer, and seismometer. Once the LRT is placed, it will continue collecting data until about 5 m away and then will resume normal operating speed of 6 km/hr. All data collected through the scientific equipment will be transmitted via UHF to the Lander, which will process the data and then communicate with the Orbiter using a Small Deep Space Transponder (SDST). (1) (3) (2)

##### *F.2.6.2.1. Telescope Deployment Path*

The maximum payload for MATHLETE is 389 kg at speeds up to 6 km/hr. With the total mass of each LRT at 3.8 kg, the total mass of all 65 LRTs is 247 kg. This enables MATHLETE to take all 65 LRTs out in one trip. The LRTs will be placed out in "Y" shaped array with a 120 degree angle between each leg as shown in Figure 14. One LRT will be placed in the center of the array and 43 LRTs on each leg of the array. The first Lander will land 1 km from the center of the array. MATHLETE 1 will leave the Lander and place the first LRT in the center of the array. After placing the first LRT, MATHLETE 1 will travel down one leg of the array, placing 43 LRTs. Next, it will travel 30 km to the end of the second leg of the array and start place the remaining 21 LRT on this leg. Calculating the total distance traveled and allowing 10 minutes to place each LRT, the total time required to place all LRTs was calculated to be approximately 20.2 hours.

The second Lander will land directly left of the center of the array as shown in Figure 14. MATHLETE will take the 65 LRTs on the Lander and traverse to the center of leg two and start placing the LRTs where the MATHLETE 1 stopped. MATHLETE 2 will complete the placement of LRTs on this leg and then place all the LRTs on the third leg of the array. The total distance required to travel by MATHLETE is calculated as 39.6 km. Allowing 10 minutes for the placement of each LRT, the total time required by MATHLETE 2 to place all telescopes is 17.3 hours.

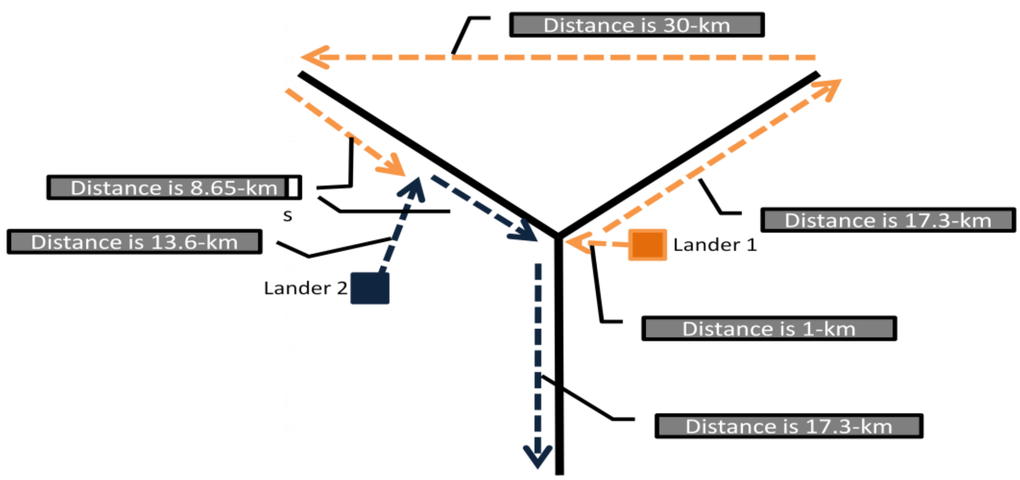


**Figure 14. Telescope Deployment Path for MATHLETE 1 and 2**

### F.2.6.3. Communications and Data Rates

The communication data rates are constrained by the amount of data transferable to the orbiter from the Lander. The maximum data rate will be 100 Mbit/s and will communicate with each Orbiter for 3000 seconds per pass, each Orbiter making 9 passes per day. The data will be transmitted via X-band from the Lander to the Orbiter in the frequency range of 7.145-7.235 GHz, and Ka-Band from the Orbiter to Deep Space Network (DSN) in the frequency range of 31.800-32.300 GHz. The SDST will be used to transmit data between the orbiter and DSN, and from DSN to the Earth. (1) (2) (3)

### F.2.6.4. Earth Based Communications

The ground systems receiving data sent from the Moon and sending commands to the orbiter will be part of the DSN, which is a part of NASA's Jet Propulsion Laboratory (JPL). The DSN has three earth based installations located in Goldstone Deep Space Communications Complex in Barstow, California; Madrid Deep Space Communication Complex located 60 kilometers west of Madrid, Spain; and the Canberra Deep Space Communications Complex located 40 kilometers southwest of Canberra, Australia. These facilities have been placed at approximately 120 degrees from one another around the Earth in an attempt to maximize satellite communication time. These three communication centers send and receive data from the Deep Space Operations Center located in Pasadena, California.(21)

## F.3. Development Approach

LI decided at the beginning of the design phase that there was going to be a strict development approach. This approach captured the over-arching philosophies and guidelines that the team would use while designing the mission. LI's Lead System Engineer (LSE) was given the role of ensuring that this approach was adhered to throughout the design phase.

### *F.3.1. Systems Engineering Approach*

#### F.3.1.1. Requirements Traceability and Management

LI decided to use at top-down design approach when beginning the mission design. The Discovery AO laid out a list of top level requirements that were viewed as the governing body of this mission. These top level requirements were then decomposed and flowed down to the CoC scientists. The CoC scientist created a Science Traceability Matrix, seen in Section D.2. The Science Traceability Matrix further decomposed the AO requirements which then flowed down to the UAHuntsville engineers as operation requirements. LI's LSE then took the operation requirements and allocated them to the appropriate subsystem teams or project partners (i.e. spacecraft and propulsion, science and technology, ESTACA). These allocated requirements were distributed to subsystem teams in team meetings and to project partners through formal Interface Requirement Documents (IRDs) that will be discussed later. LI's LSE was in charge of managing and ensure that all requirements were met at all levels of the design. Once these documents were distributed, a configuration management approach was set in order to ensure no unauthorized design changes were made.

#### F.3.1.2. System Engineering Tools

Once requirements were established for each mission element, specific design or selection of each mission element began. During the design and selection of these elements many options and questions presented themselves. Several system engineering tools were utilized in order to decide which options best suited our mission. One tool that helped these decision making processes on several occasions was the Decision Analysis. The decision analysis took Figures of Merits (FoMs), or criteria for evaluation, and gave each FoM a weight. Weights were assigned to these FoMs based on a 1-3-9 scale, where the weight of 1 was of lowest importance and the weight of 9 was of highest importance. Each design option was then assigned a rating to each of the FoM's. These ratings were on a 1- 10 scale, where the rating of 10 best satisfies the FoM and the rating of 1 least satisfies the FoM. These ratings were then multiplied by the weight of each

FoM. Once calculated, the total score for each option was summed and compared. The highest score showed which design option LI found to best suit the mission.

Other tools were also used during the development approach of this mission. As the design phase progressed, multiple mission elements were found to need physical and data interfaces. LI used a system engineering tool called an $N^2$ diagram to document all these interfaces. The information from this $N^2$ diagram eventually led to the utilization of another tool, the block diagram. The block diagram visually depicts how each of the specific elements interface. The block diagram not only depicts the interfaces inside each mission element but also the major interfaces between each separate mission element. An example of a block diagram can be seen in Section F.3.1.3.

#### F.3.1.3. Interface Control

As previously stated, LI had MATHLETE and the Orbiter designed and provided by external sources. MATHLETE was developed by the InSPIRESS Level 2 high school team while the Obiter was designed by ESTACA. With these multiple elements being created by different teams, a close evaluation was performed to see how the mission elements interacted or interfaced with each other. As stated in Section F.3.1.2, a block diagram was used to depict the data and power interfaces. In this block diagram, each mission element is shown in a different blue block. Inside each blue block, each subsystem of the element is shown in separate white blocks. Red and blue lines connect these white blocks to depict the power and data interfaces that will be required within each mission element. Additionally green, blue and orange lines, which represent different frequencies of data transmission, are seen connecting separate mission elements. These lines depict the interfaces between the different mission elements. A legend which explains the different color lines is found at the bottom of block diagram. The block diagram can be seen in Figure 15.

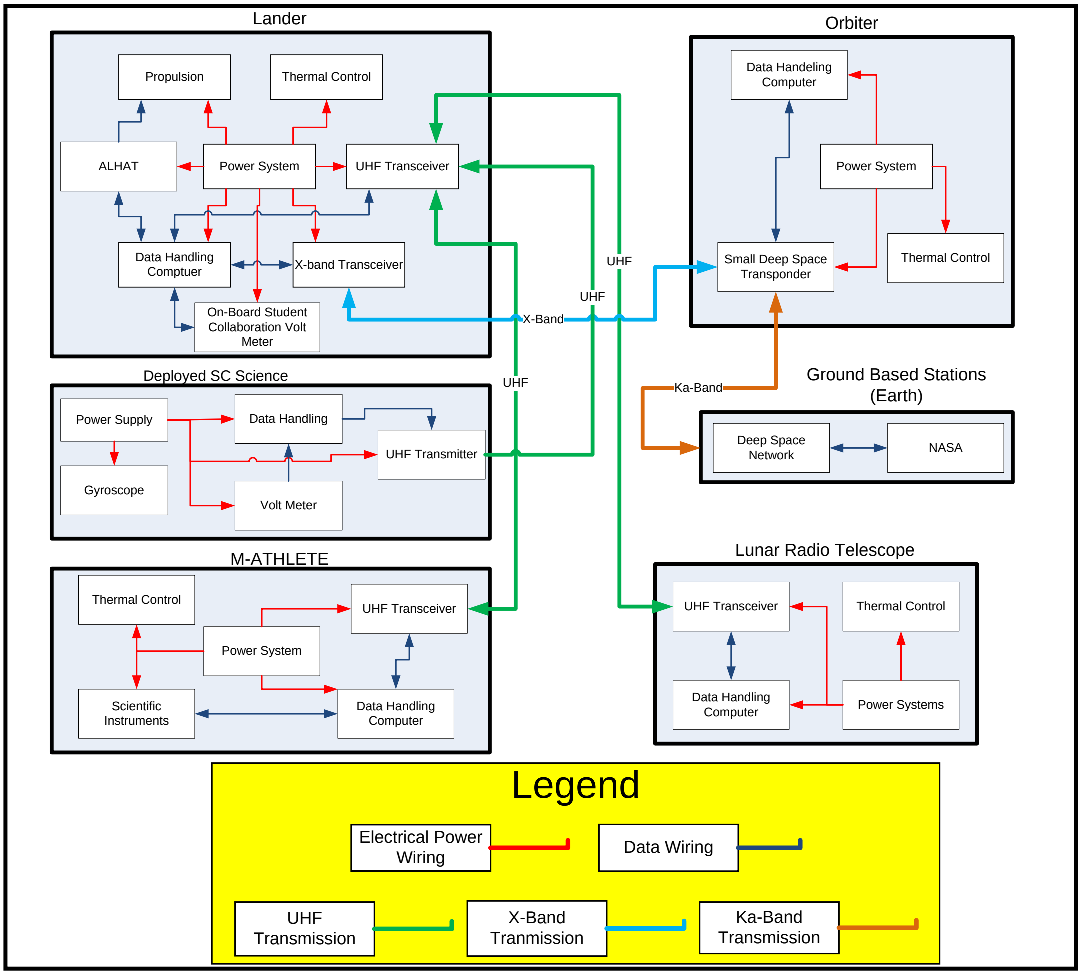


**Figure 15 - System Interface Block Diagram**

To ensure that these elements would be compatible with the system and interface correctly with the Flight Vehicle, both external teams were issued an IRD. These IRDs served as requirements documents that mapped out exactly what tasks each mission element must perform and how it must be performed. The IRDs also stated the tasks that must be performed by each team and what deliverables would be required from each team. These IRDs supplied specific dimensions and masses that the teams had to design their elements to.

### F.3.1.4. Configuration Management

LI ensured that all configurations management was handled with strict guidelines. All IRDs and other requirement documents had the following statement included, "Any major modifications to the document must be approved by the Project Manager, Principal Investigator, and Lead Systems Engineer. Changes made without approval from all parties will be considered invalid until a change is approved." See Table 17 for names and contact information of the personnel.$_{(18)}$

**Table 17. Personnel that must approve ICD requirement changes.**

| Name | Role | E-mail |
|---|---|---|
| Alexander Antonison | Project Manager | adantonison@gmail.com |
| Philip Meyer | Principal Investigator | philipcofc@gmail.com |
| Richie Nagel | Lead Systems Engineer | rkn0013@uah.edu |

### *F.3.2. Mission Assurance Approach*

The first step in establishing the mission assurance approach was to define the payload risk classification. The establishment of the risk level early in the program/project provided the basis for the project managers to develop and implement appropriate mission assurance and risk management strategies and requirements and to effectively communicate the acceptable level of risk. After considerable analysis of the mission, LI classified this mission as a Class B payload per NPR 8705.4, Risk Classification for NASA Payloads. The following methodologies were used in the mission assurance approach.

#### F.3.2.1. Fault Tolerance and Fault Management

LI estimated that in this mission the fault tolerance medium to high. The design of the mission consists of multiple redundancies and is considered quite robust. If this mission proposal is selected a system level qualitative fault tree analysis would be performed. This fault tree analysis would analyze probable failures that would cause an undesired condition during the mission. Further analysis of this fault tree would generate a more exact number of faults that the system could withstand and how these faults could be managed.

### *F.3.3. Design Maturity*

Per the Discovery AO, all mission elements were required to be based on preexisting technologies with a minimum Technical Readiness Level (TRL) of 6. LI found that to successfully achieve all mission objectives this would not be possible. Because no preexisting LRTs existed, these were given a TRL of less than 6. The MATHLETE was also given a TRL of less than 6 because it is a modification of an experimental system. This was found to be acceptable per a statement in AO paragraph *5.2.3 New Technologies /Advanced Developments* that reads, "Proposals with a limited number of less mature technologies are permitted, as long as they contain a plan for maturing all technologies to TRL 6 no later than KDP-C (Confirmation) and adequate backup plans in the event that the technologies cannot be matured as planned." As for the mission elements that were designated with a TRL of 6 or higher, these were deemed consumer off the shelf (COTS). Some mission elements were COTS with modifications that would better fit LI's mission. Further TRL discussion if found in Section F.4.

## F.4. New Technologies/Advanced Developments

The LRTs that LI has chosen were based on a theoretical crossed dipole design. The LRTs were assigned a TRL 2 because the chosen design is still in the theoretical development phase. MATHLETE, a scaled down version of the ATHLETE, has already been tested in relevant environments. Because of this, the MATHLETE was assigned TRL 5. ALHAT, with testing and verification being led by Johnson Space Center with support from the Jet Propulsion Laboratory, has been assigned a TRL 6. (16)

The LRT was chosen because of its projected attributes. These attributes include the low mass of the telescope. Because of the limited science payload, a scaled down version of this telescope will be used. LI will scale down the crossed dipole design from 5 kg to 3.8 kg. This combined with the fact that the telescopes are in the theoretical phase of development, LI assigned the LRTs a TRL 2.

LI has to implement ALHAT into this mission per its Exploration System Mission Directorate goal. ALHAT has been involved in a multiyear field testing program lead by JPL. ALHAT performs the task of scanning the topography, while simultaneously comparing gathered terrain data with topographic maps of the area which are stored in the systems data base. This gives a real-time coordinate of the lander relative to the planned course. Because of this testing of ALHAT, the system receives a TRL 6. (17)

LI shall conduct further testing on the proposed LRT design in order to address design issues and to mature the design. Tests that will be conducted will involve testing how the components operate in environments similar to the lunar surface. Tests will also be conducted to ensure that LRTs can function throughout the duration of the mission. LI shall additionally conduct further testing on MATHLETE in order to ensure that it retains the same capabilities of ATHLETE. (18) Table 18 summarizes the TRLs.

**Table 18. Technology TRL Summary for UAHuntsville Mission Elements (18)**

| Technology | TRL | Reasoning |
|---|---|---|
| **ALHAT** | 6 | Because ALHAT has been tested by JSC, JPL, and other entities in relevant environments, LI has proposed ALHAT be given a TRL 6. |
| **MATHLETE** | 5 | The ATHLETE rover has been tested in relevant environments. Because the MATHLETE is a scaled down version of the ATHLETE, the basic technology elements have been tested in relevant environments, thus LI has given it a TRL 5. |
| **LRT** | 2 | Because the crossed dipole telescope design that has been chosen has its key characteristics and applications defined along with having analytical tools that are being developed for simulation. Because of this, LI has assigned it a TRL 2. |

## F.5. Assembly, Integration, Test and Verification

### *F.5.1. Integration and Test Plan Illustration, Discussion, and Time-Phased Flow*

LI will provide test and verification plans for the Flight Vehicle. Testing will take place in Huntsville, AL at Marshall Space Flight Center. The testing and integration of components and systems into the Flight Vehicle will be subcontracted to Lockheed Martin. Testing shall take place in the respective facilities of the organizations contracted to develop the different elements. MATHLETE will have the final design, testing, and verification take place at the JPL facilities in California. (18)

### *F.5.2. Verification Approach*

LI will use the NASA System Safety Handbook verification approach. This approach will be applied in each phase of the design to ensure all requirements are met before moving into the next design phase. (18)

## F.6. Schedule Foldouts

In order to launch in November 2017, the mission starts from Pre-Phase A in June 2011. Pre-Phase A includes concept studies to do brainstorming for the project which produce multiple alternatives. LI plans to complete Pre-Phase A in 18 months. After Pre-Phase A, Phase A, "Concept and Technology Development," will determine the feasibility and desirability of ideas generated in Pre-Phase A. Phase A will establish a coherent idea of the mission. Phase B, "Preliminary Design and Fabrication," will shape the mission minutely and argue primary mission requirements. Phase A and Phase B will be completed in15 months. Phase C, "Final Design and Fabrication," will finalize the mission details, fabricate the hardware, and complete needed software. Phase C will be completed in 17 months. Phase D, "System Assembly, Test, and Launch," will assemble and test the flight elements to ensure launch readiness by the planned launch date. This phase will take 12 months to complete. On 4 November 2017, Phase E, "Operation and Sustainment," will begin with the launch of the first LV. The details of Phase E are mentioned in Section F.2. Once all mission objectives are fulfilled, Phase F, "Closeout," will take approximately 1 month. The schedule foldout is seen in Figure 16. (18)

| Phase | | | Duration |
|---|---|---|---|
| Pre-Phase A | | | 18 months |
| Phase A | | | 15 months |
| Phase B | | | 15 months |
| Phase C | | | 17 months |
| Phase D | | | 12 months |
| Phase E | Total | | 2year 6month |
| | The Spacecraft 1 | **Total** | 4day5hr4min22sec |
| | | MCC | 3day4hr53min10sec |
| | | LOI | 1min25sec |
| | | On orbit | 1day |
| | | DOI | 1sec |
| | | Brake | 1min25sec |
| | | Man | 1sec |
| | | FAL | 8min20sec |
| | The Spacecraft 2 | **Total** | 4day8hr35min12sec |
| | | MCC | 3day8hr24min |
| | | LOI | 1min25sec |
| | | On orbit | 1day |
| | | DOI | 1sec |
| | | Brake | 1min25sec |
| | | Man | 1sec |
| | | FAL | 8min20sec |
| | Science | | 3year 6month |
| Phase F | | | 1 month |

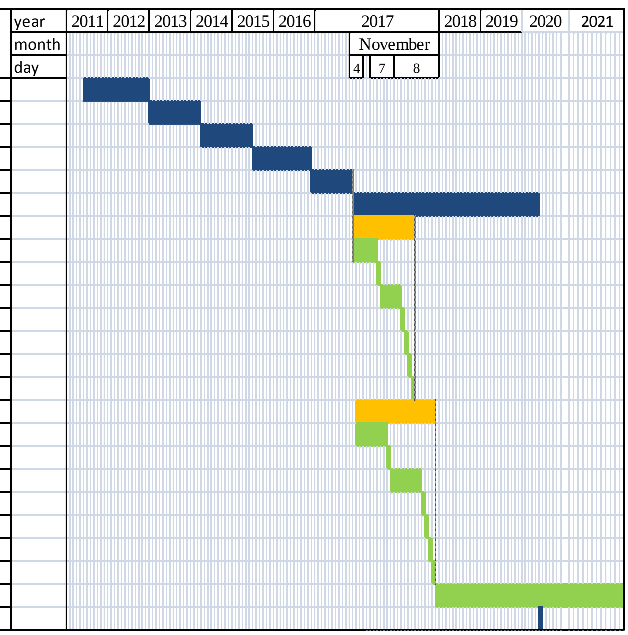


**Figure 16. Gantt Chart of Mission**

# G. Management

## G.1. Management Approach

UAHuntsville is the lead organization for this project. The engineering department at UAHuntsville is the lead for this proposal. The management positions for the engineering proposal team are Project Manager, filled by Alexander Antonison; Chief Engineer, filled by Kirby Viall; Lead System Engineer, filled by Richie Nagel; and Spacecraft and Propulsion Design Lean, filled by Loren Bridges. CoC is partnered with UAHuntsville and is responsible for the science portion of the proposal. The management position for the science proposal team is the Principal Investigator, filled by Philip Meyer, and is assisted by the Co-Investigator, filled by Jesse Snider. The Co-Investigator reports to the Principal Investigator, who then reports to the Project Manager. The Project Manager reports to UAHuntsville. This organization scheme can be seen below in Figure 17.

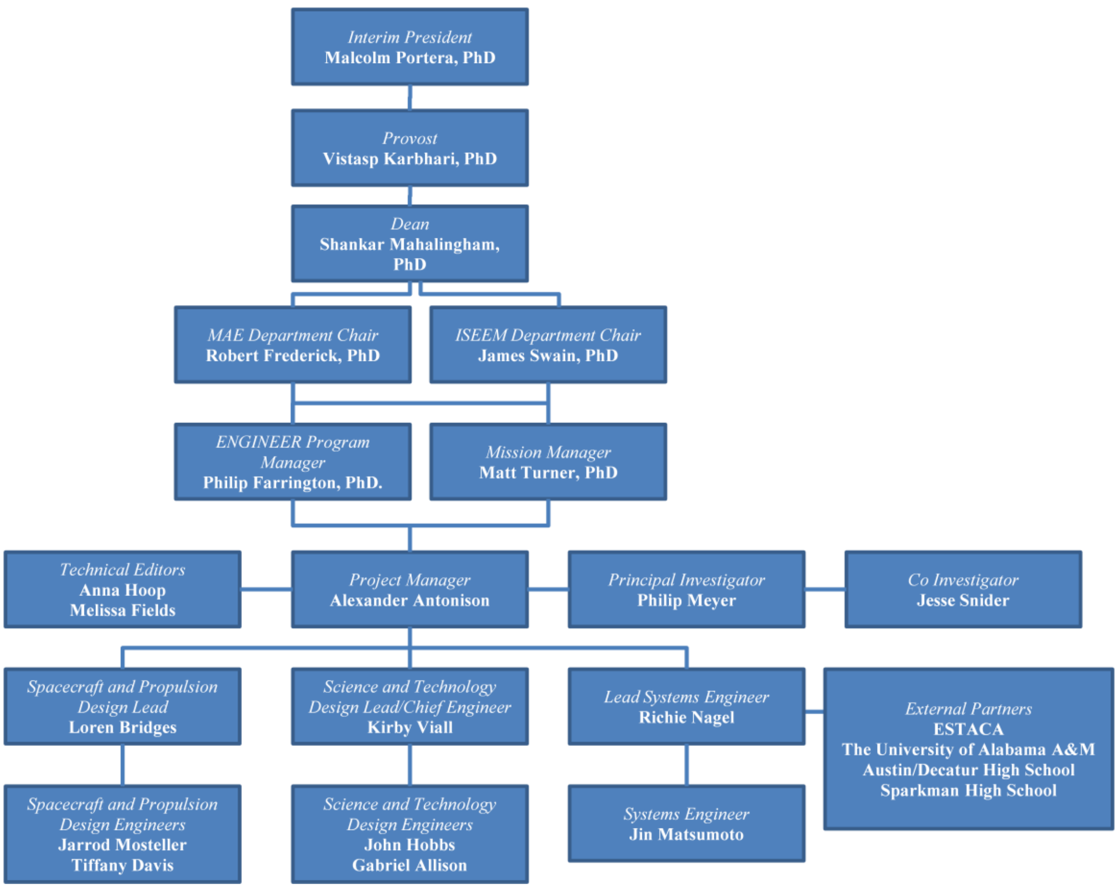


**Figure 17. Organization Management Structure**

## G.2. Roles and Responsibilities

### *G.2.1. Project Manager: Alexander Antonison*

The project manager is responsible for guiding the design process and leading the proposal team. Additionally, the project manager is responsible for all project deliverables, including the proposal.

***Project Manager Experience***

- Assistant Project Lead and Lead System Engineer for the design and fabrication of a NASA Apollo Command module flight simulator.

### *G.2.2. Principal Investigator: Philip Meyer*

The principal investigator is responsible for the formulation of the baseline and threshold science objectives and the requirements to accomplish these objectives. The principal investigator is also responsible for the science sections in the proposal.

***Principal Investigator Experience***

- Research Assistant to Narayanan Kuthriummal
  - Apply knowledge and problem solving skills to synthesize and characterize nanomaterials.
  - Build positive relationships and communications skills through collaborative research.
  - Continuously learning, through scholarly research, to meet new challenges.
- Science/Electronics Specialist
  - Work closely with researchers to design creative solutions to unique problems.
  - Expand knowledge base and technical skills through hands-on experience.

### *G.2.3. Chief Engineer: Kirby Viall*

The Chief Engineer is responsible for translating science requirements into engineering requirements. The Chief Engineer is also responsible for managing and guiding the design of all technology necessary for the mission.

***Chief Engineer Experience***

- Engineering Aide
  - Maintained company-required performance for obsolete electronic & electrical equipment
  - Provided research assistance for Department of Defense on obsolete electronic & electrical equipment.
  - Contacted manufacturers for status of electronic & electrical equipment.

### *G.2.4. Lead Systems Engineer: Richie Nagel*

The Lead Systems Engineer is responsible for managing and tracking all system requirements for the project. The Lead Systems Engineer also manages the interfacing requirements of mission elements designed by ESTACA, Alabama A&M, and Austin and Decatur High schools for UAHuntsville's mission.

***Lead Systems Engineer Experience***

- System's Engineering Intern
    - Performed specification reviews to enable requirement continuity, consistency, flowdown, and decomposition
    - Ensured appropriate verification methods and approaches were allocated to program requirements
    - Provided specification-tree framework to depict requirement baselines
    - Initiated Specification Change Notices to ensure requirement changes were properly captured and implemented
    - Facilitate Requirement management including linkages, traceability, and metrics in DOORS

### *G.2.5. Flight Vehicle and Propulsion Design Lead: Loren Bridges*

The Spacecraft and Propulsion Design Lead is in charge of guiding the design of the Flight Vehicle and propulsion systems. The Spacecraft and Propulsion Design Lead is also in charge of working with the Project Manager to allocate mass throughout all mission elements.

***Flight Vehicle and Propulsion Design Lead***

- Internship
    - Tasked with creating a working model of the cardiovascular system from abdominal aorta to femoral artery.
    - Designed system, researched necessary information, and ordered necessary components
    - Produced entire system, including modification of a chemical pump to create a pulse

## G.3. Risk Management Plan and Allocation

### *G.3.1. Mission Critical Risks*

#### G.3.1.1. Critical Mission Risks

There are many risks that must be taken into account when planning a mission which has complex and immature instruments involved. Because a more detailed risk analysis is outside the scope of this proposal, the risks identified in this section will pertain to risks that will potentially cause a mission failure. This section will also provide ways to mitigate the identified risks. These risks are tabulated in Table 21. The first column of this table is the identified risk which is an event that could cause a possible mission failure. Following this is the Risk Description column, this column goes into detail about why the aforementioned risk could potentially occur. Next is the mitigation column which is where LI proposes a possible solution that can mitigate the likelihood of the risk, whether it be through modifying the design, conducting simulations, or further analyzing the root cause of the risk. The Likelihood column rates the risk based on the scale in Table 20. This describes how likely a risk is to occur and how the possible risk mitigation solution can reduce the chance the risk will occur. The last column is the impact this risk which will have based on the scale in Table 20. This column will depict how much the said risk will endanger the mission, whether it be negligible to catastrophic. (18) Table 19 is the Risk matrix descriptions for the colors in the Risk Matrix. Figure 18 is the 5X5 Risk matrix which is a summary of Table 21.

**Table 19. Risk Matrix descriptions**

| Color | Risk Type | Description |
|---|---|---|
| | High Risk | Mission success jeopardized (immediate action required) |
| | Medium Risk | Review regularly (contingent action if does not improve) |
| | Low Risk | Watch and review periodically |

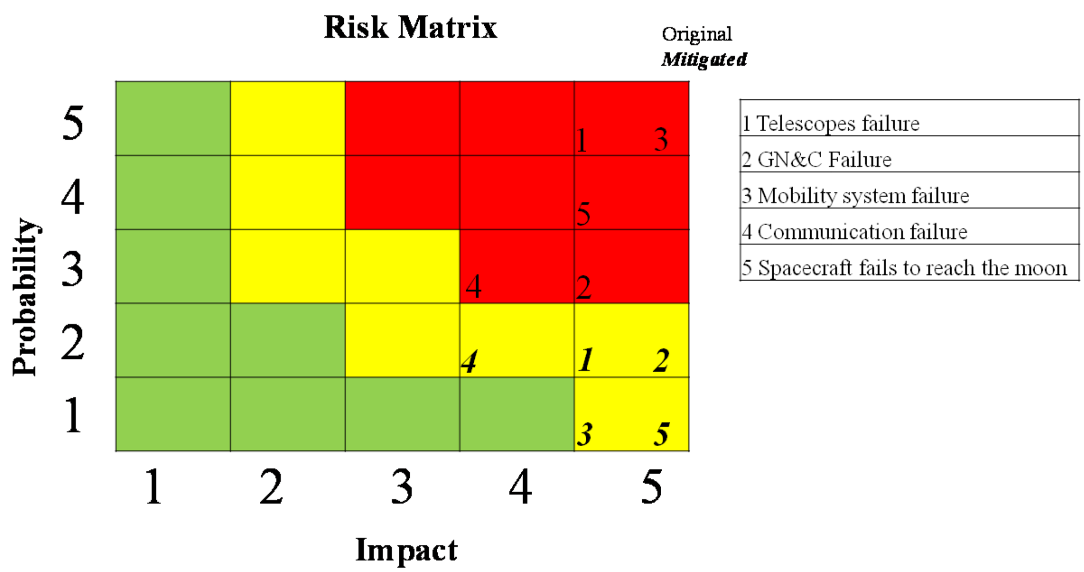


**Figure 18. 5x5 Risk Matrix**

**Table 20. Risk Assestment Scores**

| Scale | Probability of Occurrence | Impact |
|---|---|---|
| 5 | Near Certain to Occur (80-100%) | Catastrophic |
| 4 | Highly likely to Occur (60-80%) | Critical |
| 3 | Likely to Occur (40-60%) | Moderate |
| 2 | Unlikely to Occur (20-40%) | Marginal |
| 1 | Impossible (0-20%) | Negligible |

**Table 21. Critical Mission Risks**

| Risk | Risk Description | Mitigation | Impact | Likelihood |
|---|---|---|---|---|
| Over 30 of the LRTs are deployed incorrectly or malfunction. | MATHLETE could set the LRTs on uneven ground or there could be a malfunction in the LRT electronics. | Conduct additional modeling and simulation with MATHLETE placement of LRTs. Perform detailed analysis on LRTs | 5 | Original 4 Mitigated 2 |
| All Guidance Navigation and Control on board Flight Vehicle fail. | The star tracker system in the Flight Vehicle that is used to navigate the Flight Vehicle to the moon can fail; in the event this occurs, the Flight Vehicle would be unable to accurately guide itself to the moon. | A backup star tracker system is included in the Flight Vehicle as a contingency. | 5 | Original 3 Mitigated 2 |
| Mobility system falls into a crater on the lunar surface and disables the mobility system. | The Daedalus crater has many micro-craters that could potentially damage and causes a mobility system to become stuck. At this point there would be no mobility system to arrange LRT array. | The mobility system that has been chosen, MATHLETE, is capable of climbing out of craters due to its six leg design. | 5 | Original 5 Mitigated 1 |
| Communication between the lander and orbiter fails to make a connection during a single pass. | The lander may be unable to communicate all of the necessary data over the 3000 second pass due to unforeseen interference. | Lander will be capable of storing enough data to account for a failed transmission. | 4 | Original 3 Mitigated 2 |

### *G.3.2. Allocation of Resources*

The LI management team decided that the Project Manager and the Spacecraft and Propulsion Design Lead will be responsible for handling the mass reserve. This means that both must approve the allocation of the mass margin set aside for the mission. The Project Manager and the Lead Systems Engineer will be responsible for controlling and allocating the cost reserve and the schedule reserve. Only when adequate proof that an existing system requires more mass, money, or time will the margin set aside be allocated to it. The overall contingency for the mission design was set at 30%. After the design was completed, little margin was left over due to the large amount of mass required to accomplish the mission.

### *G.3.3. Descoping*

Lunar Innovations has analyzed the descoping of this mission and how this impacts accomplishing the overall mission. There are many factors that could potentially cause Lunar Innovations to descope the mission. The first factor is cost. After further analyzing the cost model, LI has come to the conclusion that it can produce one full Flight Vehicle; this includes Flight Vehicle staging, Orbiter, Lander, MATHLETE, and science payload under the 800 million dollar cost cap, the cost being $689.35 million. To launch a second full Flight Vehicle to the Moon, it will cost an additional $232.8 million. If necessary, LI can still accomplish the threshold science objectives with a single Flight Vehicle.

## G.4. Cooperative Arrangements

ESTACA designed the Orbiter that will be used to communicate with the science equipment on the far side of the Moon. Alabama A&M designed a TCaV that will be used in the Lander and Flight Vehicle propulsion systems.

# H. Cost and Estimating Methodology

## H.1. Cost Model

Lunar Innovations used the Hamaker Flight Vehicle Cost Model (22) to perform all mission cost estimates. The model consists of two main components. The first component is an extensive database of previous mission characteristics and costs. The second component is a list of input fields that require key mission characteristics to be entered. Examples of the input characteristics include dry mass, required power, design life, and cost reserve. The model then uses the entered characteristics to create an interpolating and extrapolating equation which estimates the total mission costs based on data found in the database.

To effectively utilize the Hamaker Flight Vehicle Cost Model, LI had to decide which way to approach the model. There were several different variations of how the model could be used. Initially LI thought that the best way to utilize the model was to run each of the individual mission elements in the model and sum these together to get a total Flight Vehicle cost. After doing this LI found that this unjustly increased the cost of the Flight Vehicle. Next LI attempted to run the cost model for 2 mission elements. These elements consisted of the Orbiter and the Lander. The Lander encompassed all the mission elements that would be used on the lunar surface while the Orbiter consisted of only itself. Once again, LI found that this drastically overestimated the cost of the Flight Vehicle. LI eventually found that the most appropriate way to utilize the cost model was to combine all the mission elements into one model.  This will be discussed further in Section H.2.

## H.2. Model Inputs and Output

### *H.2.1. Inputs*

LI found that there were different types of characteristics that were used in the Hamaker Flight Vehicle Cost Model. The first types of characteristics were things determined by the unchangeable aspects of the mission. Examples of these include Apogee Class, Number of Science Organizations, and Platform Factor. Table 22 shows the inputs and justifications for these mission characteristics.

**Table 22. Model Inputs and Justifications**

| Characteristic | Input | Justifications |
|---|---|---|
| Apogee Class | 3 | 3 was entered because it represents a mission beyond Geosynchronous Earth Orbit |
| Number of Science Organizations | 1 | 1 was entered because LI is using only 1 science organization, College of Charleston |
| Platform Factor | 2.2 | 2.2 was entered because the proposed mission was classified unmanned planetary mission |

The next types of inputs were characteristics that had to be thought out and determined by analyzing the planned mission. These characteristics include maximum data rate requirements, test requirements class, requirements stability class, funding stability class, team experience class, formulation study class, and new design percent. Table 23 shows the inputs and justifications for these mission characteristics.

**Table 23. Model Inputs and Justifications**

| Characteristic | Input | Justifications |
|---|---|---|
| Maximum Data Rate Requirements | 70% | LI deemed that the proposed mission would use 70% data requirements relative to state of the art being 50% and maximum being 100% |
| Test Requirements Class | 3 | 3 was entered because LI found that the proposed mission would require more average testing |
| Requirements Stability Class | 2 | 2 was entered because the proposed mission has low requirements stability |
| Funding Stability Class | 2 | 2 was entered because the mission has some funding instability |
| Team Experience Class | 3 | 3 was entered because LI's team members have average or mixed experienced levels |
| Formulation Study Class | 1 | 1 was entered because this proposed mission will require a major formulation study |
| New Design Percent | 50% | LI deemed that only 50% of the proposed mission design would be considered new design |

The last types of characteristics that LI found in the cost model were characteristics that had to be directly calculated or chosen by the science organization. These characteristics include total power generation, total dry mass, total mission design life, TRL, and cost reserves. The science team from CoC established that the mission life time had to be 4 years or 48 months. LI deemed that the cost reserve of the mission would be 30%. LI calculated the individual power generation values of each element and added these to get a total power generation value. These values can be seen below in Table 24.

**Table 24. Power Generation Values**

| Element | Power Generation (Watts) |
|---|---|
| LRT | 90 |
| Lander | 90 |
| MATHLETE | 130 |
| Orbiter | 16 |
| Total: | 326 |

The dry masses of each element were also added to get a total dry mass of the Flight Vehicle. To generate one single TRL an innovative approach was taken. LI took the mass of each element and multiplied it by the elements TRL. These values were then added to get a total "mass x TRL" value. This value was then divided by the total dry mass of the Flight Vehicle which gave a weighted average of the TRLs. The weighted TRL average was found to be 5.47. LI rounded this down to 5 to stay on the conservative side. These values can been seen in Table 25.

**Table 25. Mass and TRL Values**

| Element | Dry Mass (kg) | TRL | Mass X TRL |
|---|---|---|---|
| LRT | 247 | 2 | 494 |
| Lander | 1823 | 6 | 10938 |
| MATHLETE | 250 | 5 | 1250 |
| Orbiter | 94 | 6 | 564 |
| ALHAT | 50 | 6 | 300 |
| Totals: | 2464 | | 13546 |

Weighted TRL Average = —— = 5.47 = 5

All of the above characteristic, ones that had to be calculated or decided upon, are summarized in Table 26 below.

**Table 26. Model Inputs**

| Characteristic | Input |
|---|---|
| Total Dry Mass | 2464 kg |
| Total Power Generation | 326 W |
| Total Mission Design Life | 48 months |
| TRL | 5 |

### *H.2.2. Outputs*

All of the input values discussed in Section H.2.1 were entered into the cost model. The model then gave an output that was considered the flight vehicle cost estimate. This output was $908.9 million. LI then added the cost of the Star 48 V solid propellant engines. The first Star 48 V engine cost $3.5 million and each additional engine cost $3.25 million. (12) With a total of 2 Star 48 V engines on each flight vehicle this came to a total of $13.25 million. This was added to the $908.9 million to generate the total mission cost of $922.15 million. This cost was generated with respect to using the two proposed flight vehicles. To generate a cost estimate using one flight vehicle, LI divided the total mass and total power generation by two which would represent only one flight vehicle. All other inputs of the cost model were left the same. The cost model generated an output of $682.6 million which represented the flight vehicle cost using only one flight vehicle. $6.75 million was added for the two Star 48 V engines to give a total of $689.35. LI found that these values were realistic because the second Flight Vehicle would not cost as much as the first due to less testing and design costs. The full mission cost model estimate can be found in Section J.14.5. (22)

## **H.3. Cost Resources Allocation**

As stated above the total mission cost estimate was found to be $922.15 million. LI realized this was above the given $800 million cost cap. To achieve the threshold science objectives LI could utilize one flight vehicle for $689.35 million and stay under this cost cap. But for only $122.15 million above the cost cap, both threshold and baseline science objectives would be achieved.

# I. Acknowledgement of Education and Public Outreach & Student Collaboration

## I.1. Small Business Subcontracting Plan

Not applicable per AO Amendment.

## I.2. Education and Public Outreach

Per Requirement 55 of the Discovery AO, the following statement has been added and will be adhered to accordingly. The PI acknowledges the following statement.
"I understand the NASA SMD requirements for E/PO and I am committed to carrying out a core E/PO program that meets the goals described in the *Explanatory Guide to the NASA Science Mission Directorate Educational and Public Outreach Evaluation Factors* document. I will submit an E/PO plan with my Concept Study Report if this proposal is selected."

## I.3. Level 1 InSPIRESS High School Team Reports

### *I.3.1. Sparkman High School*

#### I.3.1.1. Science Question

Primary: If any, what are the static electric properties of lunar regolith?
Other goals (prioritized)

- -Difference between day and night
  - -Difference above, below, and on the surface
  - -In and out of the shadow, if possible

#### I.3.1.2. Approach

Approach to answering the question (Instruments Needed): volt meter, (modified by us or the team) antenna, brain, gyroscope?

- Instrument Requirements
  - o Mass, power, volume, data rates

Method of multi-crisis decision analysis:

| FOMs | Weight | Legs | House |
|---|---|---|---|
| Mass | 9 | 7 | 5 |
| Volume | 3 | 7 | 3 |
| Data | 3 | 9 | 8 |
| Durability | 9 | 5 | 7 |
| Contact | 9 | 9 | 8 |
| Simplicity | 1 | 8 | 6 |
| Lifespan | 1 | 7 | 6 |
| Objective | 9 | 1 | 4 |
| Total | | 261 | 261 |

Oddly, both solutions measured out to have the exact same efficiency, so we decided to combine them. The designs nicely complement one another and make up for each others' weaknesses. The combination of the solutions is almost guaranteed to produce usable data.

#### I.3.1.3. Overview

An overview of the solutions and how they work:

-Legged:

-consists of four probes each containing two electrical leads

-housed within the honey comb crushable pads on the lander's feet.

-When the lander's feet impact the surface of the moon, the pads will crush causing the probes to stab into the lunar surface. The probes will be connected by wires to the lander's computer and power supply. The total mass of the probes on all legs combined is 1.3 kilograms.

-"Urchin" deployed from each cardinal direction of the lander:

> -A small, grapefruit sized sphere with 6 electro sensitive probes protruding from each side that will be launched from the lander, ideally in each cardinal direction. This will be used to collect data out of the range of the lander's exhaust residue. These "urchins" will be equipped with their own power supply that will last, ideally, one lunar day, along with wireless communication and internal electronics. The mass of the four urchins total is estimated to be 8 kg.

Our chosen solution is to execute both methods because they both answer the question effectively. The legged is a simple design that requires minimal space and is reliable to answer the basic question. The more risky and complicated design—housed—provides answers to more of our questions and efficiently collects data from various locations.

We plan to remain on the surface for a total of 1 lunar day (28 Earth Days)

- Summary
  - What resources do you need from the Flight Vehicle?
    - power
    - sun sensor
    - camera
    - data processing
    - honeycomb design in legs for the crush

The probes inside of the legs would be immediately inserted into the ground as the legs are crushing up and take measurements periodically. The urchins would be deployed after the UAH landers release each box to prevent creating any obstacles for the lander. Then the probes connected to the urchin will power up and take measurements frequently.

Our projects goal is to determine the electrical properties of the lunar soil. If it is found that it is possible to send an electrical current through the lunar surface, imagine the possibilities. There would be no need for wiring; electricity could be sent from the power source directly to the required area. Of course as with any system, some sort of regulator and director would have to be designed, but this would save space on missions which equates to saving money on missions. The benefits of this experiment are not limited to the ability to transmit of power. On one of the Apollo missions to the moon an astronaut reported the soil levitating when the moon passed into shadow. If this is true then it should be possible to clean lunar vehicles and other equipment by charging its surface with electricity. Since lunar soil is very hazardous to humans when inhaled and very corrosive to lunar equipment, it would be prudent to find an easy way of removing it and disposing of it.

### *I.3.2. Guntersville High School*

In the past, NASA has reached the moon multiple times, but very little research has been done on the far side of the moon. With the upcoming mission that is reaching the far side of the moon, S.A.F.I.R.E. (Students Achieving Far-Side Intercommunications Reaching Earth) has decided to do multiple tests involving the moon's regolith. Team S.A.F.I.R.E. is composed of ten students from Guntersville High School's Fundamentals of Engineering II/III class. The team is very focused on expanding the understanding of the moon's surface material.

With the use of R.EX. (Regolith Extractor), S.A.F.I.R.E will accomplish its goal to obtain important knowledge about the regolith and provide information for further advancements in astrophysics.


**Figure 19. S.A.F.I.R.E. Team**

#### I.3.2.1. Science Objective

The R.EX. science payload will answer the following question:

**What is the heat capacity and electric charge of the moon's regolith?**

The objective of this mission is to extract regolith from the moon and use the regolith to find two unknown values: specific heat and electrical charge. Heat capacity will be determined by measuring the mass of a regolith sample (m), applying a certain amount of heat to the regolith sample (Q), and measuring the regolith sample's change in temperature during a certain time period ($\Delta T$). These values will be used to solve for specific heat capacity in the equation: $C=Q/m\Delta T$, where C is specific heat capacity. Also, electrical charge will be determined by using a volt meter.

#### I.3.2.2. Approach

After considering independent payloads, S.A.F.I.R.E decided to use an attached robotic arm, similar to the Phoenix arm used on the Mars mission as shown in Fig. 2, to collect samples and take measurements. The arm/scoop will be able to measure mass, apply heat, measure change in temperature, and determine electric potential as described in Section I.3.2.1. The following Table 27 summarizes the instruments involved:

**Table 27. Instrumentation Required**

| Instrument | Purpose |
|---|---|
| Robotic Arm | collect regolith sample |
| 500 Watt, 24v Motors (4) | provide mobility for robotic arm |
| Load Cell | measure mass of regolith sample |
| Thermocouple | measure temperature of regolith sample during a certain time period ($\Delta$T) |
| Heat Strip | heat regolith (Q) |
| Volt Meter (TECP) | measure electric charge of regolith |

#### I.3.2.3. Payload Design

The R.Ex. payload design is a robotic arm attached to a platform on top of a container connected directly to the lander. The robotic arm is based off of the Phoenix Mars Mission arm shown in Fig. 2. The arm is two tandem aluminum bars connected on the ends through a simple joint with a gear attached to the end of the joint. One side is connected to a hinge connected to a platform for stabilizing reasons. The hinge is connected to a motor allowing more reach for the arm. The other side is connected to an aluminum scoop, which is used for collecting all regolith samples. Attached to the bottom side of the scoop is a Thermal Electrical Conductivity Probe (TECP) which is used to read the electrical charge and transmit the data back. To move the arm, three motors, a gear, and a chain are used. One motor is attached to the platform where the arm is bolted down. This motor is connected via a chain to a gear at the first pivot point. A second motor has its shaft attached to the scoop, which allows the scoop to rotate. The third motor is attached to the end of the second arm between the claw and the arm. This allows the scoop to move in the vertical axis. In addition to the arm, the platform the arm is attached to is mounted on top of a container, and the arm points parallel to the ground. The container houses a miniature box inside. On the topmost of the box, a thermocouple, used to measure temperature, is extending outwards, and a heating strip is placed around it. Attached to the bottom of the box is a load cell, which measures the change in force, which accurately measures the mass.

**Table 28. Arm Mass Summary**

| Part (Material) | Mass (kg) |
|---|---|
| Long Arm Segment (Aluminum) | 53.014 kg |
| Short Arm Segment (Aluminum) | 31.809 kg |
| Motors [4] | 24 kg [6 kg/motor] |
| Scoop (Aluminum) | 1.620 kg |

| | |
|---|---|
| TECP (with kd-2 pro) | 4 kg |
| Total Arm | 114.443 kg |

**Table 29. Box Mass Summary**

| Part (Material) | Mass (kg) |
|---|---|
| Thermocouple | 0.816 kg |
| Outer Box (Aluminum) | 19.848 kg |
| Heating Strip | Negligible |
| Insolated Box (Carbon Fiber) | 11.125 kg |
| Total Box | 31.789 kg |

**Table 30. Combined Mass Summary**

| Part (Material) | Mass (kg) |
|---|---|
| Total Arm | 108.443 kg |
| Total Box | 31.789 kg |
| Combined: | 146.232 kg |

#### I.3.2.4. Concept of Operations

The segment attached to the container moves using a motor. It moves until it is perpendicular to the container and parallel to the ground. From here, the motor attached to the container rotates the chain and the gear to allow the arm to extend parallel to the ground. Then, the scoop rotates the open end towards the regolith, and both segments of the arm move down towards the regolith. The scoop enters the ground from the force of the arm. The motor attached moves the scoop in the vertical axis and begins to operate the scoop and collect regolith. Afterwards, the TECP on the bottom of the scoop probes the ground to collect data for measuring electrical charge of the regolith. The second segment moves upwards, and the first segment moves downwards to allow the scoop to return to the container. The rotational motor on the scoop turns the regolith over onto the platform. Afterwards, the arm has completed its job. Next, the load cell at the base of the platform measures the change in force which allows mass to be computed. Then, the heating strip begins to heat the sample of regolith while the thermocouple measures the change in temperature. After the test is complete, the sample is allowed to cool. Once the sample has returned to room temperature, the sample is retested to confirm the original findings.

#### I.3.2.5. Summary

This science investigation could lead to many future discoveries on the nature of far side of moon. The specific heat capacity of the regolith is an unknown value that could benefit future thermodynamic calculations involving the moon's surface. The measurements collected include mass and change in temperature and are applied to the specific heat equation ($Q=mc\Delta T$) to calculate specific heat capacity as described in Section I.3.2.1.

Additionally, knowing the electric charge of the regolith would assist scientists in future investigations of the behavior of the moon's surface. Due to the possibility of skewing data, knowing the electrical charge will help to offset the alteration that can potentially occur during any tests. While this impact may not have as large of a deal currently, where testing is all approximated, in the future, extremely accurate numbers will potentially be needed.

# J. Appendices

## J.1. Table of Proposal Participants

**Table 31. Proposal Participants**

| Partner Type | Organization | Role | Budget |
|---|---|---|---|
| Major Partners | The University of Alabama in Huntsville<br>Huntsville, Alabama, U.S. | Prime Contactor | $800 million |
| | The College of Charleston<br>Charleston, South Carolina, U.S. | Science Investigators | (Contracts UAHuntsville to manage budget) |
| Minor Partners, Vendors, and Suppliers | ESTACA<br>Paris, France | Orbiter Design | $0 |
| | Decatur High School<br>Decatur, Alabama, U.S. | Mobility System R&D | $0 |
| | Austin High School<br>Decatur, Alabama, U.S. | Mobility System R&D | $0 |

## J.2. Letters of Commitment

To Whom It May Concern:

"I acknowledge that I have been identified for institutional support of the proposed project entitled "Radio Astronomy on the Moon" on behalf of the College of Charleston, that Philip Meyer is submitting in response to the Announcement of Opportunity, #NNH10ZDA007O. I understand that the extent and justification of institutional support as stated in this proposal will be considered during peer review in determining in part the merits of this proposal. If you have any questions, please feel free to contact me at any time."

Jon Hakkila, Chair and Professor
Department of Physics and Astronomy
College of Charleston

April 20, 2011

Alexander Antonison
Project Manager
Lunar Innovations, IPT Team C
The University of Alabama in Huntsville
Mechanical and Aerospace Engineering Dept.
N274 Technology Hall
Huntsville, AL 35899

Dear Mr. Antonison,

The University of Alabama in Huntsville is pleased to formally acknowledge your team's design for a Radio Astronomy on the Moon (RAM) mission as part of NASA's Discovery Announcement of Opportunity Program. We believe, should your design be selected, the science gained from this mission will not only provide a greater understanding of our solar system, but will help to distinguish our institution as a premier center for engineering education, research, and technological development. With this said, The University of Alabama in Huntsville is fully committed to support your team in its current and future endeavors. Best wishes on being selected!

Sincerely,

Matthew W. Turner, Ph.D.
Integrated Product Team Mission Manager
The University of Alabama in Huntsville

INTEGRATED PRODUCT TEAM PROJECT OFFICE »
Shelby Center 157 301 Sparkman Drive Huntsville, AL 35899
T 256.824.2976 F 256.824.4322 http://ipt.uah.edu

## J.3. Resumes

The following pages contain the resumes of the Lunar Innovations team members.

# Gabriel Allison

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gta0001@uah.edu
982 Salty Bottom Rd.
Gurley, AL 35748


**CITIZENSHIP** U.S.

**TECHNICAL SKILLS** MATLAB, Solid Edge, NX, Excel, Mathcad 14

**EDUCATION**

**The University of Alabama in Huntsville** **Huntsville, AL**

Bachelor of Science in Engineering with a concentration in Mechanical Aerospace Engineering

Expected Graduation—May 2012

**WORK EXPERIENCE**

**Jan 2008 – Present** **Luke Allison Cabinetry** **Gurley, AL**

HVLP Operator

- High Volume Low Pressure finish spray gun
- Last in the order of Quality Control concerned with flow pattern
- Must acquire a knowledgeable eye concerned with flow rate, mixture of solute to solvent, also must gain a steady deliberate movement

**May 2006 - Nov 2006** **Industrial Process Solutions Inc.** **Decatur, AL**

Technician

- Industrial Electrical Engineering contractor specializing in Programmable Logic Controllers (PLC); use of Allen Bradley and Siemens PLC Hardware
- Maintaining as well as updating ladder logic
- Integrating new processes into existing logic
- Trouble shooting and analyzing PLC software problems and failures

**HONORS AND AWARDS**

Phi Theta Kappa

Who's Who Among American College Students

Computer Science, Math, and Technology (C.M.T.) Scholastic Scholarship, Calhoun Community College

National Dean's List 2003 and 2004

Boy Scouts of America, Elected to Order of Arrow

# Alexander Antonison

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Huntsville, AL 35810


**CITIZENSHIP** U.S.

**TECHNICAL SKILLS** Minitab, Solid Edge, NX, Arena, Microsoft Office (Visio, Project, Excel, Word, PowerPoint)

**EDUCATION**

**The University of Alabama in Huntsville** **Huntsville, AL**

Bachelor of Science in Engineering with a concentration in Industrial and Systems Engineering

GPA: 3.44/4.0 (3.72/4.0 in major), Expected Graduation—Dec 2011

**WORK EXPERIENCE**

**Mar 2010 – Present** **SMAP Center** **Huntsville, AL**

CAAS and Common Avionics (CCA) IPT Obsolescence POC
Plan, coordinate, conduct, and document meetings with manufacturers. Coordinate open actions and exchange of data information for the obsolescence analyst including Bill of Material (BOM), obsolescence Roadmaps, and notifications of obsolescence alerts to manufacturers. Maintain historical records of all relevant documented materials.

**Jul 2010 – Sep 2010** **Thermal Corporation** **Madison, AL**

Engineering Intern
Assignments included redesigning the manufacturing process of an existing product. Given the responsibility of checking and creating CAD drawings for machinery and product parts. Responsible for ordering and receiving manufacturing machinery, components, and raw materials. Tasked with assembling the machines and troubleshooting any assembly issues.

**CLEARANCE** Secret Clearance, Mar 2010 by SMAP Center

**AFFILIATIONS**

Institute for Industrial Engineers (IIE)

Society of Manufacturing Engineers (SME)

Apollo Project—The University of Alabama in Huntsville

# Loren Bridges

(256) 880-7443; (256) 682-2710
leb0007@uah.edu
732 Mountain Gap Rd.
Huntsville, AL 35803

**CITIZENSHIP** U.S.

**TECHNICAL SKILLS** Microsoft Office (Word, PowerPoint, Excel), Mathcad, MATLAB, Solid Edge

**EDUCATION**

**The University of Alabama in Huntsville** **Huntsville, AL**

Bachelor of Science in Engineering, Minor in Biology

GPA: 3.9/4.0 (4.0/4.0 in major), Expected Graduation—Aug 2011

**WORK EXPERIENCE**

**Jan 2011–Apr 2011** **The University of Alabama in Huntsville** **Huntsville, AL**

Grader and Teaching Assistant (GTA)

- Taught one lab section a week of the Kinematics and Dynamics of Machines class
- Graded weekly lab reports

**Jun 2010–Aug 2010** **The University of Alabama in Huntsville** **Huntsville, AL**

Research Assistant

- Funded by the Research and Creative Experience for Undergraduates
- Created a heart/artery system that produced blood pressure waveforms with inexpensive, non-custom components

**HONORS AND AWARDS** Dean's List

**AFFILIATIONS** Tau Beta Pi, Chair of the Website and Communications Committee

Phi Kappa Phi

# Tiffany L. Davis

256-520-7763
tld0002@uah.edu

Current Address
6235 Pulaski Pike
Huntsville, AL 35810

Permanent Address
1816 Mill Creek Rd.
Madison, AL 35757


**CITIZENSHIP**

U.S.

**TECHNICAL SKILLS**

Solid Edge, Mathcad, MATLAB, Microsoft Office 2007 (Word, Excel, and PowerPoint), Lean Six Sigma, Shop Drawings Database

**EDUCATION**

**The University of Alabama in Huntsville** **Huntsville, AL**

Bachelor of Science in Engineering with a concentration in Aerospace Engineering

GPA: 2.99/4.0, Expected Graduation—May 2011

**WORK EXPERIENCE**

**July 2010 – Present** **U.S. Army Corp of Engineers** **Huntsville, AL**

Engineering Tech YP-0802-01, U.S. Army Corp of Engineers Huntsville Center, Engineering Directorate.

- Provide general office support and assistance to the organizational unit
- Provide assistance to an upper level engineer on SpecsIntact

**June 2009 – July 2010** **U.S. Army Corp of Engineers** **Huntsville, AL**

Document Control, U.S. Army Corp of Engineers Huntsville Center, Specifications & Service Branch Engineering Directorate.

- Provided assistance to the primary document custodian
- Provided assistance in inputting data into Shop Drawing database
- Controlled in/out process of drawings, designs, and specifications

**AFFILIATIONS**

Delta Zeta

Community involvement: Liz Hurley Run and Delta Zeta Golf Tournament

# John Willis Hobbs

256-679-7581
johnw_hobbs@yahoo.com
330B County Rd. 235
Gurley, AL 35748


| | |
|---|---|
| **CITIZENSHIP** | U.S. |
| **TECHNICAL SKILLS** | Windows, Microsoft Office: Excel, Power Point, Word, MathCAD, MATLAB, PATRAN/NASTRAN, Solid Edge, FEMAP, Minitab |
| **EDUCATION** | **The University of Alabama in Huntsville** **Huntsville, AL**<br>Bachelor of Science in Engineering with a concentration in Mechanical Engineering<br>GPA: 3.602, Expected Graduation—Aug 2011 |
| **WORK EXPERIENCE** | **May 2008 –Present** **U.S. Army—AMRDEC** **Huntsville, AL**<br>Engineering Co-op<br>• Test plan formulation for full aircraft and component testing.<br>• Test data analysis<br>• Test reports<br>• Structural and fatigue analysis<br>• General technical assistance |
| **CLEARANCE** | Secret Clearance– Granted by U.S. Army - AMRDEC |
| **HONORS AND AWARDS** | Scholar—Fall 2009<br>The University of Alabama in Huntsville<br><br>Honor Scholar—Fall 2008, Spring 2009, and Fall 2010<br>The University of Alabama in Huntsville<br><br>Tau Beta Pi—Top Fifth in Engineering Class |
| **AFFILIATIONS** | American Society of Civil Engineers (ASCE)<br>The University of Alabama in Huntsville<br>Concrete Canoe Team 2010<br><br>American Society of Mechanical Engineers (ASME)<br>The University of Alabama in Huntsville<br>Moon Buggy Team 2011 |

# Jin Matsumoto

(256) 426-1406
jin.matsumoto@hotmail.co.jp

| | |
|---|---|
| Current Address | Permanent Address |
| 606 John Wright Dr. K3 | 2-128-3 Wakabadainishi |
| Huntsville, AL 35805 | Kasuga, Fukuoka 816-0823 |
| | JAPAN |
| | (092) 986-5395 |


**CITIZENSHIP** Japan

**TECHNICAL SKILLS**
Microsoft Office (Word, Excel, PowerPoint), Minitab, Arena
Operating Systems: Windows 2000, XP, Vista

**EDUCATION**
**The University of Alabama in Huntsville** **Huntsville, AL**

Bachelor of Science in Engineering with a concentration in Industrial and Systems Engineering

GPA: 3.54/4.0, Expected Graduation—Dec 2011

Integrated Product Team (IPT)

The University of Alabama in Huntsville

Radio Astronomy on the Moon

Coursework—Engineering Economy, Work Design, Management Systems Analysis, Operations Research, Statistical Quality Control, Manufacturing Systems and Facilities Design, Introduction to Systems Simulation

**PROFILE**
- Fluent writer and speaker of English and Japanese
- F-1 Visa status and OPT available

# Christopher Jarrod Mosteller

(256) 566-2157
cjm0017@uah.edu
3290 Barkley Bridge Road
Hartselle, AL 35640


**CITIZENSHP** U.S.

**TECHNICAL SKILLS** PATRAN/NASTRAN, Mathcad, MATLAB

**EDUCATION**

**The University of Alabama in Huntsville** — **Huntsville, AL**
Bachelor of Science in Engineering with a concentration in Mechanical Engineering
GPA: 3.94/4.0, Expected Graduation—Dec 2011

**Athens State University** — **Athens, AL**
Bachelor of Science in Human Resource Management
GPA: 3.80/4.0, Graduated—Aug 2006

**WORK EXPERIENCE**

**Oct 2005 – Dec 2008** — **FPMI Solutions** — **Arab, AL**
Human Resource Specialist
- Performed duties critical to supporting national homeland security needs
- Certified in conducting and auditing Federal background checks (standard form SF-86/e-QIP) for security clearances for all potential TSA officers
- Maintained daily, weekly and monthly spreadsheets, reports and databases for TSA
- Maintained PAN, Recruit Soft, Lotus Notes databases to track all recruiting
- Supplied test results, and responded to technical and administrative questions concerning the applications of candidates, assessment process, job description, salary, benefits and qualifications
- Facilitated the flow of information among TSA contractors
- Monitored local hiring process to ensure compliance with government regulations
- Acted as primary point of contact for human resource personnel at over 450 airports throughout the United States

**Jan 2005 – Oct 2005** — **Burningtree Country Club** — **Decatur, AL**
Banquet Captain
- Supervised a group of 7-10 banquet servers
- Project manager for corporate events for up to 1000 guests
- Facilitated all actions between departments to ensure appropriate timing and customer satisfaction

**HONORS, AFFILIATIONS, PUBLICATIONS**

College of Engineering Dean's List
Phi Theta Kappa
Delta Mu Delta
University of Alabama Student Launch Initiative (USLI)
American Society of Civil Engineers (ASCE)—Concrete Canoe Team

# Richie Nagel

(256) 318-1672
rkn0013@uah.edu
904 Gable Circle
Hartselle, AL 35640


**CITIZENSHIP** U.S.

**TECHNICAL SKILLS** Minitab, Solid Edge V20, Microsoft Office (Word, Excel, PowerPoint, SharePoint)

**EDUCATION**

**The University of Alabama in Huntsville** — **Huntsville, AL**
Bachelor of Science in Engineering with a concentration in Industrial and Systems Engineering
GPA: 4.0/4.0, Expected Graduation—Dec 2011

**Calhoun Community College** — **Decatur, AL**

**Auburn University** — **Auburn, AL**
Industrial and Systems Engineering

**WORK EXPERIENCE**

**Sep 2010 - Present** — **SMAP Center** — **Huntsville, AL**
Research Assistant/Engineering Intern
Provide systems engineering services for the Armed Scout Helicopter (ASH) Project Office, a division of the Program Executive Office (PEO) Aviation.

**Mar 2009 - Sep 2010** — **Martin Lawn Service LLC** — **Hartselle, AL**
Lawn Care Technician
Responsible for chemical weed control applications and fertilization.

**Feb 2008 - Oct 2008** — **Home Depot** — **Auburn, AL**
Inventory Management Associate
Responsible for inventory control, ordering stock, and price changes for four departments.

**May 2004 - Aug 2006** — **Honda Manufacturing** — **Lincoln, AL**
Co-op Student (May 2004-Aug 2004, Jan 2005-Aug 2005, May 2006- Aug 2006)
Worked in three departments of Quality Division including Parts Quality, Parts Quality – New Model, and Quality Analysis. Responsibilities included contacting suppliers, vehicle quality inspections, and warranty and problem reports. Worked in Frame Assembly Department – Process Group. Responsibilities included redesigning assembly zone process layouts and rearranging processes to improve efficiency, quality, and safety.

**CLEARANCE** Secret Clearance, Sep 2010 by SMAP Center

**HONORS**
Alpha Lambda Delta Honor Society – Auburn University
Lambda Sigma Honor Society – Auburn University
Boy Scouts of America Eagle Scout

# Kirby W. Viall
(256) 513-0409
kirbywviall2388@gmail.com
2024 North Memorial Parkway, Apartment F6
Huntsville, AL 35810

| | |
|---|---|
| **CITIZENSHIP** | U.S. |
| **TECHNICAL SKILLS** | MATLAB, Mathcad, Minitab, Nastran, Patran, Solid Edge, Simulink,<br>Microsoft Office (Word, Excel, PowerPoint) |
| **EDUCATION** | **The University of Alabama in Huntsville** **Huntsville, AL**<br>Bachelor of Science in Engineering with a concentration in Mechanical Engineering<br>GPA: 3.067/4.0, Expected Graduation--Jul 2011 |
| **WORK EXPERIENCE** | **May 2009 – Aug 2010** **Stanley Associates** **Redstone Arsenal, AL**<br>Obsolescence Researcher<br>• Assisted the engineering department in regard to product design.<br>• Maintained company-required performance/maintenance records for electronic & electrical equipment. |
| **CLEARANCE** | Secret Eligibility, Jul 2009 by DISCO |
| **AFFILIATIONS** | Integrated Product Team (IPT)<br>The University of Alabama in Huntsville<br>Radio Astronomy on the Moon<br><br>Strategically Tuned Absolutely Resilient Structures (STARS)<br>The University of Alabama in Huntsville<br><br>American Society of Civil Engineers (ASCE)<br>The University of Alabama in Huntsville<br>Concrete Canoe Team |

# Jesse Snider

(843) 224-0865
Jrsnider87@gmail.com

Department of Computer Sciences
College of Charleston
Charleston, SC 29424

159 Alexander Street Apt. B
Charleston, SC 29403

CITIZENSHIP United States of America

TECHNICAL SKILLS Software: Windows and Linux OS, Microsoft Office suites, Python, Java, Javascript, PHP/MySQL, HTML, XML, and Netbeans and Python IDLE IDEs

Certifications: A+ IT Professional

EDUCATION College of Charleston — Charleston, SC

Bachelor of Science in Computer Science

Expected Graduation: May 2011

WORK EXPERIENCE

February 2011 – Present — College of Charleston — Charleston, SC

Web Developer

Developing a website for the Religious Studies Department.

Provides students and scholars with historic data about churches in Iceland.

Utilizes HTML, JavaScript and PHP/MySQL

December 2010 – Present — Dog and Horse Fine Art — Charleston, SC

Web Developer

Manage a website for an art gallery.

Adding and editing HTML code.

August 2010 – November 2010 — Hawkes Learning Systems — Charleston, SC

Technical Support Intern

Provided technical support to customers via telephone and e-mail.

Performed in house alpha testing.

Developed troubleshooting skills for PC and Mac based systems

May 2007 – August 2007 — Carolina Youth Development Center — Charleston, SC

IT Intern

Responsible for installing and troubleshooting hardware, software and maintaining server systems.

Assisted in refurbishing and selling old computer systems to staff.

Worked on Windows XP workstations and Windows Server 2003 domains

# Philip M. Meyer, Jr.

H - (843) 789-4073 | C - (843) 343-2274
philipcofc@gmail.com

Department of Physics and Astronomy
College of Charleston
Charleston, SC 29424

144 Hester Street
Charleston, SC 29403


**CITIZENSHIP** United States of America

**TECHNICAL SKILLS** Software: Microsoft and Mac OS, Microsoft Office and iWork suites, Mathematica, MATLAB, LabVIEW, SpectraSuite, Igor Pro, XPP, Neuron, Inkscape, and LaTeX.

Specialized Equipment: Scanning electron microscope, UV-Vis photo-acoustic, FTIR, absorption, reflectance, and resonant ultrasound spectrometers.

**EDUCATION** College of Charleston — Charleston, SC

Bachelor of Science in Physics, Concentration: Energy Production

Minor: Mathematics, Expected Graduation: May 2011

**WORK EXPERIENCE** May 2009 – Present — College of Charleston — Charleston, SC

Research Assistant

- Apply knowledge and problem solving skills to synthesize and characterize nanomaterials.
- Build positive relationships and communications skills through collaborative research.
- Continuously learning, through scholarly research, to meet new challenges.

June 2010 – Present — College of Charleston — Charleston, SC

Science/Electronics Specialist

- Work closely with researchers to design creative solutions to unique problems.
- Expand knowledge base and technical skills through hands-on experience.

Fall 2008 – Present — College of Charleston — Charleston, SC

Teaching Assistant

- Cultivate communications skills through effective listening and clearly explaining physical concepts for students of diverse academic backgrounds.

April 2004 – March 2010 — Mistral Restaurant — Charleston, SC

Manager

- Developed leadership skills while managing customer focused service operations.
- Implemented SOPs and developed an employee education program that successfully increased sales.

**AFFILIATIONS** Member of the American Physical Society

## TAN Soon Lee

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soon-lee.tan@estaca.eu

RESIDENCE LA DORMERIE 81B
54 RUE DES DOCTEURS CALMETTE ET GUERIN
53000 LAVAL
FRANCE

25, JALAN BERINGIN 8
TAMAN RINTING
81750 JOHOR BAHRU
MALAYSIA


**MALAYSIAN**

**TECHNICAL SKILLS**

Software: CATIA V5; SolidWorks; MATLAB; NASTRAN; BlockSim

Skills: C programming

Projects: Design and performance of a supersonic business jet; Studies on dependability of FADEC system; Building up a quadrotor.

**EDUCATION**

**ESTACA** **Laval, France**

Engineering degree, specialized in Aeronautics, expected graduation in September 2012.

**WORK EXPERIENCE**

**July 2008 – August 2008** **Mega Auto Car Service Center** **Johor Bahru, Malaysia**

Garage worker

- Car maintenance and repair

**Jun 2010 – August 2010** **NDT Expert** **Toulouse, France**

French-Mandarin Translator

- Translated training materials of Non-Destructive Testing in aeronautical sector. Translated methods included Penetrant Testing (PT), Ultrasonic Testing (UT) and Magnetic particle Testing (MT)

**PUBLICATIONS** -

**HONORS AND AWARDS** -

**AFFILIATIONS** -

**Lebernicheux Brice**

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Current Address
165 chemin lintier
Vallauris , France , 06220

Permanent Address
35 rue René Brice
Rennes, France , 35200

**CITIZENSHIP**

**TECHNICAL SKILLS**

MS office, CATIA V5, MATLAB

**EDUCATION**

Fourth year student at ESTACA University (one of the leading French engineering universities specialized in the transport sector : Automotive, Aeronautical, Space & Railway engineering), Laval

Major: Aeronautics

Course program includes: Aerodynamics , Helicopter, Thermodynamic , Quality, Plane performance , Avionic , Electrical Machine...

**WORK EXPERIENCE**

**Month Year – Month Year** **Name of Company** **City, State**

2010 (12 weeks) → Internship Coordinator of research program PARADISAEA at Objectif Sciences International

Research and Conception of an ULM with solar energy

2008 (4 weeks) → Mechanic in the Technical center of Rennes (SNCF)

Repair of pneumatics valves for TGV

2007 (5 weeks) → Mechanic in the Technical center of Rennes (SNCF)

Resolution of the breakdowns of access doors of TER

2007 to 2010 → Micro-company of animation

2006 (2 weeks) → Assistant charter for Edmiston&Company

Assistant charter of yacht in an English company

**Adrien GUILLEMIN**

22 rue André Citroën,
92300 Levallois-Perret
France

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E-mail: adrien.guillemin@hotmail.fr

**STUDENT IN AEROSPACE ENGINEERING**

Serious, quick learner and patient.

**REASEARCH AND DEVELOPMENT OF ROCKET**

-Calculated performance
-Dimensioned structure
-Established mission phases
-Analyzed satellite orbit

**ENGINEERING SCIENCES**

-Analyzed mechanic stress, thermodynamic flow and electric circuits
-Calculated statistics
-Surveyed manufacturing processes
-Planned projects
-Solved mechanic problems by means of Finite Element Analysis

**PROGRAMMATION**

-Translated mathematic equations to Simulink models
-Program Matlab
-Prepared using PATRAN/NASTRAN
-CAD with CATIA

## EMPLOYMENT

| | | |
|---|---|---|
| July 2008: | Internship, | Dassault Aviation, Argenteuil, France |
| July 2006: | Internship, | Dexia Group, Paris, France |

## Education

ESTACA, Levallois, France.

Courses: Space mechanic, signal processing, GNC (Guidance, Navigation, Control).

Project: supersonic bizjet.

**Thibaut Cretois**

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53470 Martigné sur Mayenne
FRANCE



Le Poirier
53470 Martigné sur Mayenne
FRANCE


**CITIZENSHIP** France

**TECHNICAL SKILLS** CATIA, Solid Works, MATLAB

**EDUCATION**

**L'École Supérieure des Techniques Aéronautiques et de Construction Automobile** — **Laval, France**

Aeronautical Engineering

**WORK EXPERIENCE**

**June 2010 – July 2010** — **Saica Pack Laval** — **Laval, France**

Summer Job

**June 2009 – July 2009** — **MP Sérigraphie** — **Martigne, France**

Summer Job

- Packaging and putting into pallet of printing documents

**AFFILIATIONS** (professional/educational organizations first, then collegiate (non technical/educational) and community involvement)

## J.4. Summary of Proposed Program Cooperative Contributions (N/A)

Not Applicable per AO Requirement Amendment.

## J.5. Draft International Participation Plan – Discussion on Compliance with U.S. Export Laws and Regulations (N/A)

Not Applicable per AO Requirement Amendment.

## J.6. Planetary Protection Plan and/or Sample Curation Plan

### *J.6.1. Planetary Protection Plan*

In accordance with the Planetary Protection Requirement, the Flight Vehicle will be constructed in a bio-free zone and will also be decontaminated with a UV light decontamination phase.

### *J.6.2. Sample Curation Plan*

No samples will be returned to Earth from the Moon.

## J.7. Discussion of End of Mission Flight Vehicle Disposal Requirements

All science equipment on the lunar surface will remain there after the mission's duration. Once the end of life command is given to the orbiter, it shall allow its orbit to decay and will crash into the lunar surface.

## J.8. Compliance with Procurement Regulations by NASA PI Proposals (N/A)

Not applicable due to Amendment.

## J.9. Master Equipment List

| Citation Number | Subsystem | Equipment | Mass [kg] | Quantity | Total Mass [kg] | Heritage |
|---|---|---|---|---|---|---|
| 6 | Science Instruments (MATHELTE) | Geophones | 0.2 | 2 | 0.2 | Apollo 16 |
| 7 | | GPR | 0.045 | 2 | 0.045 | Titan |
| 8 | | Magnetometer | 0.075 | 2 | 0.075 | Juno |
| 9 | Power (Lander) | Lander Power | 31.39486415 | 2 | 31.39486415 | None |
| 9 | Power (LRT) | Solar Panel | 0.25 | 130 | 16.25 | None |
| 9 | | Secondary Battery | 1.8 | 130 | 117 | None |
| 9 | Propulsion (Lander) | Propulsion Lander | 113.021511 | 16 | 904.1720876 | None |
| 9 | Propulsion (Flight Vehicle) | Stage I Star 48 V | 2164.06 | 2 | 2164.06 | Conestoga 1 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 10 | ACS (Lander) | RAD 750 | 0.55 | 2 | 0.55 | |
| 10 | ACS (MATHLETE) | RAD 750 | 0.55 | 2 | 0.55 | |
| 13 | ACS (Flight Vehicle) | MR-106L | 0.59 | 24 | 7.08 | None |
| 9 | Thermal (Lander) | MLI | 14.12768887 | 2 | 14.3242 | Standard |
| 9 | Thermal (LRT) | Thermal Control | 0.16 | 130 | 10.4 | None |
| 15 | Structures (Flight Vehicle) | Piping | 3.24 | 2 | 3.24 | Standard |
| 15 | | Adapter | 20 | 6 | 60 | Standard |
| 9 | Structures (Lander) | Harness | 3.3 | 2 | 3.3 | Standard |
| 9 | | Mechanical | 495.7261 | 2 | 495.7261 | None |
| 9 | | Main Thruster | 489.7598808 | 4 | 979.5197616 | Standard |
| 9 | | Fuel Tank | 23.82 | 6 | 71.46 | Standard |
| 13 | | Pressure Tank ATK Part Number 80386-101 | 89.568 | 6 | 268.704 | HS-601 Xenon |
| 5 | Structures (Telescopes) | Box | 0.58 | 130 | 37.7 | None |
| 5 | | Horn Antenna and Mechanism | 0.5 | 130 | 32.5 | None |
| 5 | | >2m dipoles | 0.85 | 260 | 221 | None |
| 19 | GN&C (Flight Vehicle) | Flight Vehicle GN&C | 3.264 | 2 | 3.264 | Standard |
| 19 | GN&C (Lander) | GN&C | 3.263742 | 2 | 3.263742 | Standard |
| 2 | Comm (Lander) | Small Deep Space Transponder | 3 | 2 | 3 | Phoenix (Spacecraft) |
| 3 | | ANT-2.4-OM-CM-01-N (Antenna) | 1.5 | 4 | 3 | None |
| 1 | | NanoCom UHF Half-duplex Transceiver | 0.012 | 4 | 0.024 | None |
| 1 | Comm (MATHELTE) | NanoCom UHF Half-duplex Transceiver | 0.085 | 4 | 0.17 | None |
| 4 | Comm (LRT) | ANT-868-JJB-xx (Antenna) | 0.075 | 130 | 9.75 | None |
| 1 | | NanoCom UHF Half-duplex Transceiver | 0.12 | 130 | 15.6 | None |

| | | | | | | |
|---|---|---|---|---|---|---|
| 8 | MATHLETE | MATHLETE | 2340 | 2 | 4680 | None |
| 8 | ALHAT | ALHAT | 50 | 2 | 100 | None |
| | Structures (Orbiter) | MLI | 2.6 | 2 | 5.2 | Standard |
| | | Chassis | 17.5 | 2 | 35 | Standard |
| | On board Computer (Orbiter) | Reaction Wheels | 12 | 2 | 24 | Standard |
| | | Gyros | 7.1 | 2 | 14.2 | Standard |
| | | OSCAR OBC | 5.2 | 2 | 10.4 | Standard |
| | PCS | Solar Arrays + Wheels | 20 | 2 | 40 | Standard |
| | | Batteries | 4.4 | 2 | 8.8 | Standard |
| | TCS | Heater | 0.5 | 2 | 1 | Standard |
| | DATA | Storage | 14 | 2 | 28 | Standard |
| | | Transponder | 3.2 | 2 | 6.4 | Phoenix (Spacecraft) |
| | | Antenna | 5.37 | 2 | 10.74 | Standard |
| | Propulsion | Thruster | 0.65 | 2 | 1.3 | Standard |

## J.10. List of Abbreviations and Acronyms

**Table 32. Acronym Definitions**

| Acronym | Phrase |
|---|---|
| ACS | Attitude Control System |
| ALHAT | Autonomous Landing Hazard Avoidance Technology |
| AO | Announcement of Opportunity |
| AU | Astronomical Unit |
| AVUG | Atlas V Launch Services User's Guide |
| Brake | Braking Burn |
| CME | Coronal Mass Ejections |
| CoC | The College of Charleston |
| Co-I | Co-Investigator |
| COTS | Consumer Off the Shelf |
| DOI | De-Orbit Initiation |
| DSN | Deep Space Network |
| EA | Environmental Assessment |
| EIS | Environmental Impact Statement |
| ESTACA | École supérieure des techniques aéronautiques et de construction automobile |
| FAL | Final Approach and Landing |
| GN&C | Guidance, Navigation, and Control |
| ISM | Interstellar Medium |
| JPL | Jet Propulsion Laboratory |
| LOI | Lunar Orbit Insertion |
| LRT | Lunar Radio Telescope |
| LSE | Lead System Engineer |
| LV | Launch Vehicle |

| | |
|---|---|
| MATHLETE | Mini All-Terrain Hex-Limbed Extra-Terrestrial Explorer |
| MCC | Mid-Course Correction |
| MLI | Multi-Layer Insulation |
| NSSDC | National Space and Science Data Center |
| OBC | On Board Computer |
| PFL | Payload Faring |
| PI | Principle Investigator |
| PM | Project Manager |
| PMF | Propellant Mass Fraction |
| PSR | Payload Separation Ring |
| RAM | Radio Astronomy on the Moon |
| SC | Structural Capabilities |
| SDST | Small Deep Space Transponder |
| SEO | Science Enhancement Option |
| SRM | Solid Rocket Motor |
| TCaV | Throttling Cavitating Venturi Valve |
| TLI | Trans Lunar Injection |
| TRL | Technology Readiness Level |
| UAHuntsville | The University of Alabama in Huntsville |
| UHF | Ultra High Frequency |
| ULA | United Launch Alliance |
| AKR | Auroral Kilometric Radiation |
| VLB | Very Large Baseline |
| CME | Coronal Mass Ejections |
| IPM | Interplanetary Medium |
| ISM | Interstellar Medium |
| RAM | Radio Astronomy on the Moon |
| AU | Astronomical Unit |
| IF | Intermediate Frequency |
| CRUX | Construction & Resource Utilization Explorer |
| MECA | Mars Environmental Compatibility Assessment |
| NSSDC | National Space and Science Data Center |
| PDS | Planetary Data System |
| CDF | Common Data Format |

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## J.12. NASA-Developed Technology Infusion Plan

Encompassing the scope of the mission as a whole there is but one component or system or telescope or anything else that can be solely attributed to NASA's development. The system owed NASA, ALHAT, will perform the imperative task of acting as the lander's eyes in order for this mission to take place. The ALHAT system was developed by NASA and has been successfully integrated into LI's proposed RAM mission. Aside from ALHAT there are no other technologies developed through NASA. (

## J.13. Description of Enabling Nature of ASRG (N/A)

Not applicable because not using ASRG.

## J.14. Calculations

### *J.14.1. Propulsion Design Equations*

$$M_P = M_o\left(1 - e^{\frac{-\Delta V}{9.81 * I_{sp}}}\right)$$

| Maneuver | $M_o$(kg) | $M_p$(kg) |
|---|---|---|
| MCC | X | Through use of rocket equation, gives Y |
| LOI | X-Y | Through use of rocket equation, gives Z |
| DOI | X-Y-Z | Through use of rocket equation, gives W |
| Brake | X-Y-Z-W | Through use of rocket equation, gives V |
| Man | X-Y-Z-W-V | Through use of rocket equation, gives T |
| FAL | X-Y-Z-W-V-T | Through use of rocket equation, gives usable mass |

| Subsystem | Percentage of Mass (%) |
|---|---|
| Payload | 30.24 |
| Mechanical | 27.34 |
| Propulsion | 6.31 |
| Power | 1.75 |
| GN&C | 0.18 |
| Thermal | 0.79 |
| Communications | 0.09 |
| Harness | 3.33 |

Brown

### *J.14.2. Orbital Thermal Design*

Temperature Range $293K$ or $303K$

Max Power Dissipation $Q_W := 3000W$

Using only Lander for surface area: $4.25m \cdot 4.25m \cdot 2 + 4.25m \cdot 2m \cdot 4 = 70.125m^2$

Sphere diameter with that surface area: $\left(\frac{70.125m^2}{\pi}\right)^{.5} = 4.725m$

Properties Based on Teflon: $\alpha_s := .31($

$\varepsilon_{IR} := .\varepsilon$

Earth, Moon Radiation Properties:

$$G_s := 1413\frac{W}{m^2} \qquad q_{IR} := 237\frac{W}{m^2} \qquad a := .3$$

$$\sigma := 5.67 \cdot 10^{-8}\frac{W}{m^2 \cdot K^4} \qquad R_E := 6378km \qquad H := \frac{384403km}{2}$$

$$K_a := .657 + .54 \cdot \frac{R_E}{R_E + H} - .196\left(\frac{R_E}{R_E + H}\right)^2$$

View Factor, Sphere to Earth: $$F_s := .5 \cdot \left[1 - \frac{\left(H^2 + 2 \cdot H \cdot R_E\right)^{.5}}{H + R_E}\right]$$

Max Temperature:

$$T_{max} := \left[ \frac{\frac{G_s \cdot \alpha_s}{4} + q_{IR} \cdot \varepsilon_{IR} \cdot F_s + G_s \cdot a \cdot \alpha_s \cdot K_a \cdot F_s + \frac{Q_W}{\pi \cdot ((4.725m))^2}}{\sigma \cdot \varepsilon_{IR}} \right]^{.25}$$

$T_{max} = 241.571K$

$Q_W := 500W$

Minimum Temperatuer:

$$T_{min} := \left[ \frac{q_{IR} \cdot \varepsilon_{IR} \cdot F_s \cdot .5 + \frac{Q_W}{\pi \cdot (4.725m)^2}}{\sigma \cdot \varepsilon_{IR}} \right]^{.25}$$

$T_{min} = 112.062K$

Because Temperatures are low, the body mounted radiator can keep the Lander thermally stable

Radiator Area:

$$A_{rad} := \frac{1500\,W}{\sigma \cdot \varepsilon_{IR} \cdot (298K)^4} = 4.193m^2$$

Cold Temperature for Radiator:

$$\left( \frac{500W}{A_{rad} \cdot \sigma \cdot \varepsilon_{IR}} \right)^{.25} = 226.431K$$

That temperature is too cold, according to the limits: A heater and thermal louveres will be used on the lander

### *J.14.3. Cavitating Venturi Valve Design*

#### J.14.3.1. Valve Sizing

In order to meet the engine requirements for fuel delivery, the team needed to assess the flow characteristics of the TCaV to determine if it could deliver the needed amount of propellant (hydrazine) to the engine. To determine the appropriate orifice size for the valve, an Equivalent Sharp Edged Orifice Diameter or ESEOD was calculated. The ESEOD tells us what flow path size internal to the valve is needed in order to flow a fluid of a particular density at a given pressure and flow rate. Applying a valve sizing software by Valcor which uses the following equation, we calculate the ESEOD for a valve that will deliver the required flow rate for the Aeroject MR-80B:

$$q = C_d A \sqrt{(2gh_L)}$$

where,

$q$ = flow rate, in cubic feet per second
$C_d$=Discharge coefficient (0.93 for TCaV)
$A$=flow area in square feet
$g$=gravity
$h_L$=head loss in feet of water

Based on this calculation, TCaV will provide a flow rate of 9.25 lb/s (4.2 kg/s) of hydrazine with an inlet pressure of 300 psia. This gives a maximum ESEOD of 0.464in. The current configuration of TCaV provides a maximum ESOD with the pintle fully retracted of 0.467in. Therefore, no internal modifications of TCaV would be needed to meet the MR-80B requirements.

#### J.14.3.2. TCaV Design Concept

Interface Requirements: TCaV will require a 2 inch line size. Welding is the preferred method of fastening as it will allow for a significant reduction in mass at the interfaces.

Materials: TCaV will be made using 304L Stainless Steel and Monel.

Actuator Interface: An Electro-mechanical actuator will be used to drive to TCaV pintle.

The following illustrations constitute the conceptual TCaV proposed for use with the MR-80B engine for this mission. Figure 20 is the assembled valve. Figure 20 is a cross section showing the internal geometry. This concept is not the team's final design but is similar to the design that is being proposed for manufacturing. The stress analysis that follows is based on this concept. However, the structural thicknesses listed in the stress analysis spreadsheet (Appendix A) will reflect the required thicknesses needed for the NASA's flight requirements. The internal geometries are the same and satisfy the needs of the proposed engine configuration.

##### *J.14.3.2.1. The End Cap*

While some of the material that makes the end cap can be removed, it cannot be reduced too much. The first design idea for the end cap is to weld the end cap to the body. This is oppose to using bolts, which is the current design for the mating of the feature to its body. If welded, this will cut out the need for any screws/bots. Welding also then leaves the possibility that the thickness of the lip of the end cap can be reduced. The second proposed redesign is to minimize the size of the lip directly as well as reduce the number of bolts and/or the size of the bolts being used. Last is the proposed idea to extend the innermost section of the end cap to eliminate the change in diameter between the tip of the end cap and its mated surface with the body. This will allow for the end cap to serve the purpose of housing the pintle and keep the pintle aligned without having unnecessary material.

The final design that was selected was to weld the end cap to the body. Welding of this part will allow for a better seal of the parts together and it's cheaper to manufacture. There was not much that was able to be changed because of the requirements needed for the actuator, and also for an easier manufacturing process. Once the requirements were met then calculations were done to prove that the redesign that was done will actually be capable of being made and capable of being used in an actual flight.

##### *J.14.3.2.2. The Body*

This feature will interface with both of the other components. Similar to the other components, the strategy is to get rid of as much excess material as possible with as minimal impact to the interfaces as possible. The corners of the body are over designed and as a result, material will be removed. Fluid initially enters the body at the location marked propellant inlet in Figure 20. The reduction in material of the body was taken primarily from the inlet port walls and from replacing the inlet flange with a prepared end for welding to a 2 inch line. The exit connections (at the seat and end cap) of the body have the limiting factor of only being able to reduce as far as the mating areas of the features connecting to them.

##### *J.14.3.2.3. The Seat*

The strategy for the seat was to optimize mass reduction by segmenting the seat and performing stress analyses on each segment. This was done because the diameter profile of the seat is not constant and therefore the stresses varied from end to end. This allows us to optimize the wall thickness based on the variation in the diameters along the length of the seat. Another mass reduction opportunity was replacing the engine interface flange with a tube stub for welding to the engine inlet. The inner diameters cannot be changed however, because it will change the proper functioning of the valve. The seat walls will be very thin and will have to be reinforced by machining gussets at the wall near the body interface. This will protect against line loads such as torque and bending moments.

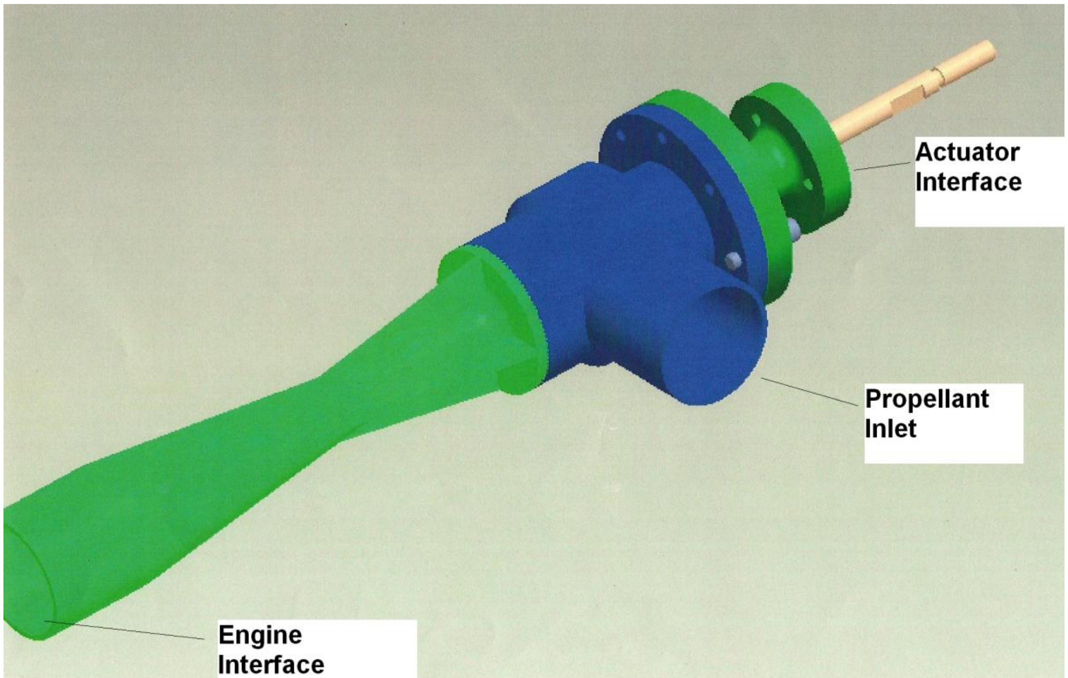


**Figure 20. TCaV Assembly**

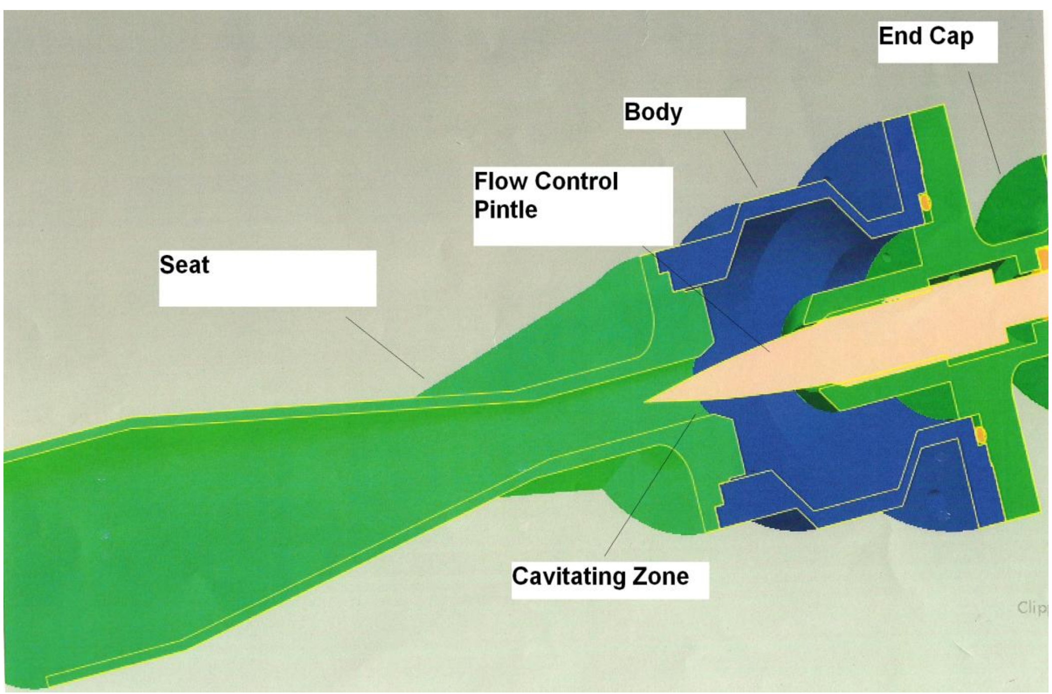


**Figure 21. TCaV Cross Section**

### J.14.3.3. Stress Analysis

Structural integrity of TCaV was assessed based on pressures and loads given from NASA's requirements. The following requirements are used for this analysis:

***Pressure***

Maximum Design Pressure (MDP) will be 2000 psig

Proof Pressure will be 1.5 times MDP = 3000 psig

Burst Pressure will be 2.5 times MDP = 5000 psig

Proof Factor of Safety=1.1

Burst Factor of Safety=1.4

***Materials***

| | Yield (psi) | Ultimate (psi) |
|---|---|---|
| 304L | 25,000 | 70,000 |
| Monel | 55,000 | 84,000 |

Stresses created by pressure loads for TCaV were calculated using the following equations:

**Longitudinal Stress:**

$$\sigma 1_i := \frac{P_i \cdot FS \cdot R_i^{\ 2}}{R_o^{\ 2} - R_i^{\ 2}}$$

**Maximum Hoop Stress at inner most point**

$$\sigma 2_i := P_i \cdot FS \cdot \left( \frac{R_o^{\ 2} + R_i^{\ 2}}{R_o^{\ 2} - R_i^{\ 2}} \right)$$

**Radial Stress:**

$$\sigma 3_i := -P_i \cdot FS$$

**Sheer Stress:**

$$\sigma shear_i := P_i \cdot \frac{R_o^{\ 2}}{R_o^{\ 2} - R_i^{\ 2}}$$

Where,
P = inlet pressure
Ro=Outer diameter

Ri=Inner diameter
FS=Factor of safety

Since the combined loads (pressure and line loads) are not yet fully defined, body dimensions in Appendix A only reflect pressure loads.

### *J.14.4. Power Systems Design*

#### J.14.4.1. Lander

##### *J.14.4.1.1. Solar Panel*

**Table 33. Lander Solar Panel Design**

| | | | |
|---|---|---|---|
| Edge Length (m) | 0.25 | m | |
| Area | 0.0625 | m^2 | |
| Sun Gives | 1447 | W/m^2 | at 90 Degrees |
| Power | 90.4375 | W | |
| HOURS OF SUN per day cycle | 334.7402778 | hr | |
| w-hr needed | 20479.2 | | |
| w-hr generated using above edge length | 30273.07387 | W-hr per 14 day 'day cycle' | |
| Mass of Solar Panel | 0.25 | kg | |

#### J.14.4.2. Mobility System

##### *J.14.4.2.1. Solar Panel*

**Table 34. Mobility System plus Contingency for the science equipment and InSPIRESS**

| | | | |
|---|---|---|---|
| Edge Length (m) | 0.3 | m | |
| Area | 0.09 | m^2 | |
| Sun Gives | 1447 | W/m^2 | at 90 Degrees |
| Power | 130.23 | W | |
| HOURS OF SUN per day cycle | 334.7402778 | hr | |
| w-hr needed | 168.8295 | | |
| w-hr needed w/30% contingency | 219.47835 | | |
| w-hr generated using above edge length | 43593.22638 | W-hr per 14 day 'day cycle' | |
| Mass of Solar Panel | 0.36 | kg | |

### *J.14.5. Cost Model Input Tables*

**Table 35. One LV Cost Model**

| | | | |
|---|---|---|---|
| Enter Flight Vehicle Bus + Instruments Total Dry Mass | **2464** | | KG |
| Enter Flight Vehicle Total Power Generation Capacity (LEO Equivalent) | **326** | 326 | W LEO equivalent flux |
| Enter Design Life in Months | **48.00** | | Months |
| Enter Number of Science Organizations | **1.0** | 1 | Count (Enter zero for projects with no science or science organization involvement) |
| Enter Apogee Class | **3.0** | | LEO=1, HEO/GEO=2, beyond GEO=3, Planetary=4 |
| Enter Maximum Data Rate Requirements Relative to SOTA Expressed as Percentile | **70%** | | Kbps requirement relative to the state-of-the-art for the ATP date expressed as a percentile where 0%=very low, 50%=SOTA, 100% is maximum |
| Enter Test Requirements Class | **3.0** | | Less than average testing=1, Average=2, More than average=3, Extensive=4, Very extensive=5 |
| Enter Requirements Stability Class | **2.0** | | Very low volatility=1, Low=2, Average=3, High=4, Very high volatility=5 |
| Enter Funding Stability Class | **2.0** | | Stable funding=1, Some instability=2, Significant instability=3 |
| Enter Team Experience Class [Derived from Price Model; used with permission from Price Systems LLP] | **3.0** | | Extensive experience=1, Better than average=2, Average (mixed esperience)=3, Unfamiliar=4 [Ref: Price Model] |
| Enter Formulation Study Class | **1.0** | | Formulation study (1=Major, 2=Nominal, 3=Minor) |
| Enter New Design Percent | **50%** | | Simple mod=30%, Extensive mod=70% (average), New=100% |
| Enter ATP Date Expressed as Years Since 1960 | **51** | | Years elapsed since 1960 |
| Regression Model Result | $203.6 | | DDT&E + TFU (Phases C/D/E) in Millions of 2004 Dollars including fee, excluding full cost |
| ---------------------------------------------------------------------------- | ---------------------------------------------- | Factor | ------------------------------------------------------------------------------------------ |
| Enter Technology Readiness Level (TRL) Penalty Factor | **5.0** | 1.30 | Refer to NASA TRL scale (TRL 6 is nominal) |
| Enter Platform Factor [Derived from Price Model; used with permission from Price Systems LLP) | **2.20** | 1.27 | Platform factor (Airborne Military=1.8, Unmanned Earth Orbital=2.0, Unmanned Planetary=2.2, Manned Earth Orbital=2.5, Manned Planetary=2.7) [Ref: Price Mdoel] |
| Enter Functional Complexity Factor | **To Be Added Later** | 1.00 | To be added later |

| | | | |
|---|---|---|---|
| Subtotal (Non Full Cost Subtotal) | **$335.7** | ----- | Subtotal (Millions of 2004 Dollars including fee) |
| Calculated Size of the Government Project Office (Project Office Only--Excludes Government Functional Line/Laboratory Labor) | **58.6** | ----- | Civil service annual full time equivalents (FTE's) |
| Enter Override of Calculated Government FTEs (or leave zero to accept calculated size of project office) | **50.00** | ----- | Civil service annual full time equivalents (FTE's) |
| Final Estimate of the Size of the Government Project Office and other Oversight (excludes government non-oversight labor which is included in subtotal above) | **50.0** | ----- | Civil Service Full Time Equivalents (FTE's) |
| Enter Civil Service Loaded Annual Labor Rate Including Center and Corporate G&A | **$215,000** | ----- | Thousands of 2004 Dollars |
| Calculated Project Phase C/D Schedule Duration (Excludes O&S Phase E) | **57** | ----- | Months |
| Enter Override of Calculated Phase C/D Schedule Duration (or leave zero to accept calculated duration) | **27** | ----- | Months |
| Final Estimate of the Project Phase C/D Schedule Duration | **27** | ----- | Months |
| Calculated Cost of the Government Project Office | **$51.4** | ----- | Millions of 2004 Dollars |
| Government Service Pool Use Intenstiy Factor | **3** | 0.0900 | 1=Minimum use of service pools, 2=Less than average, 3=Average, 4=More than average, 5=Significantly more than average |
| Calculated Cost of Government Service Pool Use | **$30.2** | ----- | |
| Enter Override of Calculated Cost of Government Service Pool Use (or leave zero to accept calculated service pool cost) | **$0.0** | | |
| Final Estimate of the Cost of Government Service Pool Use | **$30.2** | | |
| Subtotal (2004$) | **$417.3** | | |
| Ground System | **$37.6** | | |

| | | | |
|---|---|---|---|
| Enter Override of Calculated Ground System Cost | **$0.0** | | |
| Final Estimate of the Cost of Ground System | **$37.6** | | |
| Subtotal (2004$) | **$454.8** | | |
| Enter Launch Services Cost | **$0.0** | | |
| Enter Cost Reserves | **$136.5** | | |
| Total (2004$) | **$591.3** | | |
| Total (2010$) | **$682.6** | | |

**Table 36. Two LV Cost Model**

| Mission Characteristic | **Input** | Factor | Description |
|---|---|---|---|
| Enter Flight Vehicle Bus + Instruments Total Dry Mass | **4928** | | KG |
| Enter Flight Vehicle Total Power Generation Capacity (LEO Equivalent) | **652** | 652 | W LEO equivalent flux |
| Enter Design Life in Months | **48.00** | | Months |
| Enter Number of Science Organizations | **1.0** | 1 | Count (Enter zero for projects with no science or science organization involvement) |
| Enter Apogee Class | **3.0** | | LEO=1, HEO/GEO=2, beyond GEO=3, Planetary=4 |
| Enter Maximum Data Rate Requirements Relative to SOTA Expressed as Percentile | **70%** | | Kbps requirement relative to the state-of-the-art for the ATP date expressed as a percentile where 0%=very low, 50%=SOTA, 100% is maximum |
| Enter Test Requirements Class | **3.0** | | Less than average testing=1, Average=2, More than average=3, Extensive=4, Very extensive=5 |
| Enter Requirements Stability Class | **2.0** | | Very low volatility=1, Low=2, Average=3, High=4, Very high volatility=5 |
| Enter Funding Stability Class | **2.0** | | Stable funding=1, Some instability=2, Significant instability=3 |
| Enter Team Experience Class [Derived from Price Model; used with permission from Price Systems LLP] | **3.0** | | Extensive experience=1, Better than average=2, Average (mixed esperience)=3, Unfamiliar=4 [Ref: Price Model] |
| Enter Formulation Study Class | **1.0** | | Formulation study (1=Major, 2=Nominal, 3=Minor) |
| Enter New Design Percent | **50%** | | Simple mod=30%, Extensive mod=70% (average), New=100% |

| | | | |
|---|---|---|---|
| Enter ATP Date Expressed as Years Since 1960 | **51** | | Years elapsed since 1960 |
| Regression Model Result | $275.0 | | DDT&E + TFU (Phases C/D/E) in Millions of 2004 Dollars including fee, excluding full cost |
| --------------------------------------------------------------------------- | ---------------------------------------------- | Factor | ------------------------------------------------------------------------------------- |
| Enter Technology Readiness Level (TRL) Penalty Factor | **5.0** | 1.30 | Refer to NASA TRL scale (TRL 6 is nominal) |
| Enter Platform Factor [Derived from Price Model; used with permission from Price Systems LLP) | **2.20** | 1.27 | Platform factor (Airborne Military=1.8, Unmanned Earth Orbital=2.0, Unmanned Planetary=2.2, Manned Earth Orbital=2.5, Manned Planetary=2.7) [Ref: Price Mdoel] |
| Enter Functional Complexity Factor | **To Be Added Later** | 1.00 | To  be added later |
| Subtotal (Non Full Cost Subtotal) | **$453.5** | ----- | Subtotal (Millions of 2004 Dollars including fee) |
| Calculated Size of the Government Project Office (Project Office Only--Excludes Government Functional Line/Laboratory Labor) | **72.4** | ----- | Civil service annual full time equivalents (FTE's) |
| Enter Override of Calculated Government FTEs (or leave zero to accept calculated size of project office) | **50.00** | ----- | Civil service annual full time equivalents (FTE's) |
| Final Estimate of the Size of the Government Project Office and other Oversight (excludes government non-oversight labor which is included in subtotal above) | **50.0** | ----- | Civil Service Full Time Equivalents (FTE's) |
| Enter Civil Service Loaded Annual Labor Rate Including Center and Corporate G&A | **$215,000** | ----- | Thousands of 2004 Dollars |
| Calculated Project Phase C/D Schedule Duration (Excludes O&S Phase E) | **69** | ----- | Months |
| Enter Override of Calculated Phase C/D Schedule Duration (or leave zero to accept calculated duration) | **27** | ----- | Months |
| Final Estimate of the Project Phase C/D Schedule Duration | **27** | ----- | Months |
| Calculated Cost of the Government Project Office | **$61.4** | ----- | Millions of 2004 Dollars |

| | | | |
|---|---|---|---|
| Government Service Pool Use Intenstiy Factor | **3** | 0.0900 | 1=Minimum use of service pools, 2=Less than average, 3=Average, 4=More than average, 5=Significantly more than average |
| Calculated Cost of Government Service Pool Use | **$40.8** | ----- | |
| Enter Override of Calculated Cost of Government Service Pool Use (or leave zero to accept calculated service pool cost) | **$0.0** | | |
| Final Estimate of the Cost of Government Service Pool Use | **$40.8** | | |
| Subtotal (2004$) | **$555.7** | | |
| Ground System | **$50.0** | | |
| Enter Override of Calculated Ground System Cost | **$0.0** | | |
| Final Estimate of the Cost of Ground System | **$50.0** | | |
| Subtotal (2004$) | **$605.7** | | |
| Enter Launch Services Cost | **$0.0** | | |
| Enter Cost Reserves | **$181.7** | | |
| Total (2004$) | **$787.4** | | |
| Total (2010$) | **$908.9** | | |

**Table 37. CoC Cost Model**

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| COLLEGE OF CHARLESTON | | | | | | | | | |
| Science Team RAM Team C | | 12 Months | 12 months | 12 months | 12 months | 12 months | 12 months | 12 months | |
| 2017 - 2023 | | Year 1 | Year 2 | Year 3 | Year 4 | Year 5 | Year 6 | Year 6 | |
| | | FY11 | FY12 | FY13 | FY14 | FY15 | FY16 | FY16 | TOTAL |
| | | | | | | | | | |
| | Effort | 20.00% | 20.00% | 20.00% | 20.00% | 20.00% | 20.00% | 20.00% | |
| Salaries | | | | | | | | | |
| Philip M. Meyer, Jr. [PI] | Acad Year | $80,000 | $80,000 | $92,000 | $92,000 | $92,000 | $92,000 | $92,000 | $620,000 |
| | Summer | $25,000 | $25,000 | $38,000 | $38,000 | $38,000 | $38,000 | $38,000 | $240,000 |
| Jesse Snider [Co-I] | Acad Year | $80,000 | $80,000 | $80,000 | $92,000 | $92,000 | $92,000 | $92,000 | $608,000 |
| | Summer | $25,000 | $25,000 | $25,000 | $38,000 | $38,000 | $38,000 | $38,000 | $227,000 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | $25,000 | | | | | | | |
| Students (TBD) | Grad-Acad Year | $14,000 | $14,000 | $14,000 | $14,000 | $14,000 | $14,000 | $14,000 | $98,000 |
| | Grad-Acad Year | $14,000 | $14,000 | $14,000 | $14,000 | $14,000 | $14,000 | $14,000 | $98,000 |
| | Undergrad-Sum | $3,000 | $3,000 | $3,000 | $3,000 | $3,000 | $3,000 | $3,000 | $21,000 |
| | UndergradSum | $3,000 | $3,000 | $3,000 | $3,000 | $3,000 | $3,000 | $3,000 | $21,000 |
| Total Salaries: | | $269,000 | $244,000 | $269,000 | $294,000 | $294,000 | $294,000 | $294,000 | $1,958,000 |
| | | | | | | | | | |
| Fringe benefits (list rates) | | | | | | | | | |
| Co-I - Acad Year (30%) | 30.00% | $48,000 | $48,000 | $51,600 | $55,200 | $55,200 | $55,200 | $55,200 | $368,400 |
| Co-I - Summer (24%) | 24.00% | $12,000 | $12,000 | $15,120 | $18,240 | $18,240 | $18,240 | $18,240 | $112,080 |
| Student - Grad and Acad Yr | 1.60% | $280 | $280 | $280 | $280 | $280 | $280 | $280 | $1,960 |
| Student Undergrad Summer | 9.00% | $540 | $540 | $540 | $540 | $540 | $540 | $540 | $3,780 |
| Total Fringe Benefits: | | $60,820 | $60,820 | $67,540 | $74,260 | $74,260 | $74,260 | $74,260 | $486,220 |
| | | | | | | | | | |
| Total Salaries and Fringe: | | $329,820 | $304,820 | $336,540 | $368,260 | $368,260 | $368,260 | $368,260 | $2,444,220 |
| | | | | | | | | | |
| Equipment | | | | | | | | | |
| Mac Pro | | $14,916 | $0 | $0 | $0 | $0 | $0 | $0 | $14,916 |
| Mac Pro | | $14,916 | $0 | $0 | $0 | $0 | $0 | $0 | $14,916 |
| | | | | | | | | | |
| Total Equipment | | $14,916 | $0 | $0 | $0 | $0 | $0 | $0 | $14,916 |
| | | | | | | | | | |
| Materials, supplies | | | | | | | | | |
| Printing / Office Supplies | | $1,053 | $870 | $872 | $888 | $888 | $888 | $888 | $6,347 |
| | | | | | | | | | |
| Total Supplies | | $1,053 | $870 | $872 | $888 | $888 | $888 | $888 | $6,347 |
| | | | | | | | | | |
| Subcontracts | | | | | | | | | |
| UAH | | $919,070,301 | $0 | $0 | $0 | $0 | $0 | $0 | $919,070,301 |
| Total Subcontracts | | $919,070,301 | $0 | $0 | $0 | $0 | $0 | $0 | $919,070,301 |
| | | | | | | | | | |
| Travel | | | | | | | | | |
| IAC and ADASS Mtgs (2/ yr) | | $5,000 | $5,000 | $5,000 | $5,000 | $5,000 | $5,000 | $5,000 | $35,000 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Team Mtgs | | $2,000 | $2,000 | $2,000 | $2,000 | $2,000 | $2,000 | $2,000 | $14,000 |
| Total Travel | | $7,000 | $7,000 | $7,000 | $7,000 | $7,000 | $7,000 | $7,000 | $49,000 |
| | | | | | | | | | |
| Total Direct Costs | | $919,423,090 | $312,690 | $344,412 | $376,148 | $376,148 | $376,148 | $376,148 | $921,584,784 |
| | | | | | | | | | |
| Indirect Costs | | | | | | | | | |
| (40% TDC) | | $178,468 | $147,715 | $162,700 | $177,692 | $177,692 | $177,692 | $177,692 | $666,575 |
| | | | | | | | | | |
| TOTAL COFC COST: | | $919,601,558 | $460,405 | $507,112 | $553,840 | $553,840 | $553,840 | $553,840 | $922,251,359 |
| | | | | | | | | | |
| | | | | | | | | | |
| **Signatures:** | | | | | | | | | |
| | Philip Meyer, Jr. | | | PI, Lunar Innovations | | | | | |
| **Date:** | Apr 21, 2011 | | | | | | | | |

Philip M Meyer Jr